PB84-179878

Characterization of Emissions from a Fluidized-Bed Wood Chip Home Heating Furnace

Research Triangle Inst.
Research Triangle Park, NC

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Mar 84

U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-179878

EPA-600/7-84-038
March 1984

Characterization of Emissions from a Fluidized-Bed Wood Chip Home Heating Furnace

by

R. S. Truesdale
Research Triangle Institute
P.O. Box 12194
Research Triangle Park, NC 27709

EPA Contract No. 68-02-3170-70

EPA Project Officer: Michael C. Osborne

Industrial Environmental Research Laboratory
Research Triangle Park, North Carolina 27711

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-84-038	2.
3. RECIPIENT'S ACCESSION NO. PB84 179878	
4. TITLE AND SUBTITLE Characterization of Emissions from a Fluidized-bed Wood-chip Home Heating Furnace	5. REPORT DATE March 1984
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Robert S. Truesdale	8. PERFORMING ORGANIZATION REPORT NO. RTI/1914-70-01F
9. PERFORMING ORGANIZATION NAME AND ADDRESS Research Triangle Institute P. O. Box 12194 Research Triangle Park, North Carolina 27709	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO. 68-02-3170, Task 70
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Final; 4/82 - 5/83
	14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Michael C. Osborne, Mail Drop 65, 919/541-4113.

16. ABSTRACT The report gives results of measurements of emissions from a residential wood-chip combustor, operated in both a fluidized-bed and cyclone-fired mode, and their comparison with those from a conventional woodstove and industrial wood-fired boilers. In general, the combustion efficiency of the fluidized-bed and cyclone-fired wood-chip burner is higher than that of conventional woodstoves. Concomitant with this increase in efficiency is a decrease in most emissions. For the fluidized-bed tests, significant reductions of total hydrocarbons and CO were observed, compared to woodstove emissions. The cyclone test showed PAH levels far below those of conventional woodstoves, approaching levels measured in industrial wood-fired boilers. A baghouse, installed during two fluidized-bed tests, was extremely effective in reducing both particulate and PAH emissions. Method 5 samples from above the fluid bed suggest that appreciable PAH is formed in the upper region of the furnace or in the watertube heat exchangers. In general, the cyclone-fired mode was more effective in reducing emissions from residential wood combustion than the fluidized-bed mode.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution, Hydrocarbons	Pollution Control	13B, 07C
Wood Wastes, Dust	Stationary Sources	11L, 11G
Wood, Carbon Monoxide	Wood Chips	07B
Combustion, Particles	Wood Stoves	21B, 14G
Stoves, Boilers	Baghouses	13A
Fluidized-bed Processors, Fabric Filters		13I, 11E
Cyclone Separators		

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 74
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ABSTRACT

Emissions from a residential wood chip combustor, operated in both a fluidized bed mode and a cyclone-fired mode, were measured and are compared to emissions from a conventional woodstove and industrial wood-fired boilers. In general, the efficiency of combustion for the fluidized bed and cyclone-fired wood chip burner is higher than that for conventional woodstoves. Concomitant with this increase in efficiency is a decrease in most emissions. For the fluidized bed tests, significant reductions of total hydrocarbons and carbon monoxide were observed compared to the woodstove emissions. For the cyclone tests, even more reduction over the emissions of a conventional woodstove was achieved for hydrocarbons and carbon monoxide. Particulate and nitrogen oxide emissions were slightly higher for both the fluidized bed and for the cyclone combustors as compared to the conventional woodstoves. Polycyclic aromatic hydrocarbon (PAH) emissions were higher for the fluidized bed tests than for the conventional woodstoves, with respect to the heavier PAH compounds. The cyclone test, however, showed PAH levels far below those of conventional woodstoves, approaching levels measured in industrial wood-fired boilers. A baghouse installed during two of the fluidized bed tests was extremely effective in reducing particulate emissions and reducing PAH emissions as well. Method 5 samples taken above the fluid bed suggest that appreciable PAH formation occurs in the upper region of the furnace or in the water tube heat exchangers. In general, the cyclone-fired mode was more effective in reducing emissions from residential wood combustion than the fluidized bed mode.

TABLE OF CONTENTS

Section		Page
Abstract		iii
List of Figures		v
List of Tables		vi
Acknowledgments		vii
1.0	Introduction	1
2.0	Equipment and Fuel	4
3.0	Sampling Procedures--Organics	7
4.0	Analytical Procedures	11
	4.1 Gas Analysis	11
	4.2 Organic Analysis	11
	4.2.1 Sample Preparation	11
	4.2.2 Total Organics	12
	4.2.3 PNA Analysis--Gas Chromatography	12
5.0	Experimental	15
6.0	Results	17
	6.1 Particulate Emissions	17
	6.2 Carbon Monoxide Emissions	18
	6.3 NO_x Emissions	21
	6.4 Hydrocarbon Emissions	21
	6.5 PAH Emissions	23
7.0	Conclusions	29
References		30
Appendix A--Final Report, "Fluidized Bed Home Heating Furnace," prepared by ETS, Inc., Roanoke, VA, September 1982		A-1
Appendix B--Additional Data.		B-1

LIST OF FIGURES

Number		Page
1	Fluidized bed home heating system schematic	5
2	Comparison of particulate emission factors.	19
3	Comparison of carbon monoxide emission factors.	19
4	Comparison of NO_x emission factors.	22
5	Comparison of total hydrocarbon emission factors.	22

LIST OF TABLES

Number		Page
1	Fuel Characteristics	6
2	Sample System	9
3	Chromatographic Conditions	13
4	Operating Parameters	16
5	Emission Factors	17
6	Comparison of Orsat and GC CO Measurements	20
7	Emission Factors, PAH Compounds	24
8	PAHs in Baghouse Particulate	26
9	PAH Emission Factors for Woodstove and Industrial Wood-Fired Boilers	27

ACKNOWLEDGMENTS

This work was supported under the Conventional Combustion Environmental Assessment Program of the U.S. Environmental Protection Agency, Contract No. 68-02-3170. Special thanks to Scott Harkins and Keith Leese for their able assistance during sampling and analysis, and to J. K. Burchard for reviewing the manuscript.

1.0 INTRODUCTION

The use of woodstoves for domestic heating has become increasingly popular in recent years. Woodstoves have been installed at the rate of one million per year since 1977,[1] and the trend is expected to continue because of the rising cost of oil and gas, and the increased awareness of the need to find an alternative to these nonrenewable fuels. However, ambient air studies have revealed that a significant decline in air quality is attributable to residential combustion of wood.[2 3 4 5 6]

Emissions from the combustion of solid fuels for home space heating that are of primary concern are particulates, volatile hydrocarbons, and carbon monoxide, which are products of incomplete combustion. Wood combustion emissions are generally higher from residential combustion sources than from other combustion units (such as industrial boilers) because of the relatively low combustion efficiency of most residential units and typical operating conditions which are conducive to incomplete combustion.[7] In addition, industrial combustion units are often equipped with emission control equipment, such as multiple cyclones for particulate emission reduction.[8] Residential combustion of gas and oil also produces lower levels of these emissions than the use of wood, which is attributable to the differences in the nature of the fuels[7] and to differences in combustion conditions.

Particulates from the combustion of wood in domestic heating units consist of inorganic ash, carbon chars, and condensable organics.[9] Residential combustion of wood is considered to be a major source of ambient particulates in several localities.[2 3 4 5 6] A large portion of particulate from residential combustion of wood is inhalable (less than 2.5 μm in diameter).[9] In Missoula, Montana, ambient particulate levels have been linked to health problems of grade school students and persons with pulmonary diseases.[5]

Levels of particulate emissions are highly variable and depend upon factors such as fuel and equipment types, firing rate, and burn rate.[9 10 11]

Organic particulate emissions from combustion of wood in woodstoves have been found to decrease with increasing burn rate, increasing moisture content of wood, increasing log size, increasing heat release rate, and increasing stack gas temperature.[11] [12]

A variety of condensable organic species may be produced as a result of incomplete combustion or pyrolysis of organic materials in fuels. Polynuclear aromatic hydrocarbons (PAH), aldehydes, aliphatic hydrocarbons, and phenolic compounds are some of the organic species identified in emissions from residential combustion of wood.[9] PAH emissions are a major concern because many PAH compounds (polynuclear aromatics) have proven to be potent animal carcinogens.

In 1976, PAH from residential combustion of wood counted for 80 percent of total PAH from all sources,[13] and woodstove PAH emissions have been found to be higher than those from fireplaces.[7] One reason for the relatively high levels of PAH from residential stoves is that maximum thermal efficiency usually requires that air flow through the stove be reduced to a minimum. These oxygen-starved combustion conditions are favorable to the formation of PAH compounds.

It must be emphasized that total PAH emissions are not necessarily indicative of carcinogenic risks, since not all PAH compounds are carcinogenic.[14] However, several suspect carcinogens have been identified in emissions from residential combustion of wood.[15] [16] [17]

Carbon monoxide (CO) is also a byproduct of incomplete combustion. The effects of low levels of CO on the central nervous and cardiovascular systems are well known. CO is of particular concern because large amounts of CO enter the atmosphere from many combustion processes, and CO emissions exceed those of all other atmospheric pollutants except CO_2.[18] Although motor vehicles are the major source of CO, CO emissions from woodstoves are significant. Emissions from woodstoves are far in excess of CO emissions from all other residential heating units,[7] including fireplaces, as well as from industrial wood or bark boilers.[19]

Formation of nitrogen oxides (NO_x) is dependent upon fuel nitrogen content, the amount of air introduced into the stove, combustion temperature, and type of combustion equipment.[7] NO_2 is thought to be the most toxic of

the nitrogen oxides, producing local irritation at low levels and lung injury at higher levels.[20] NO_x is also of environmental concern because nitric acid precipitates formed from atmospheric NO_x have had adverse effects on terrestrial and aquatic ecosystems. NO_x is also known to react with environmentally prevalent amines to form N-nitroso compounds, many of which are potent animal carcinogens.[21]

Total NO_x emissions from residential combustion of wood are substantially lower than total emissions from domestic heating units fueled with oil and gas,[8] reflecting the greater use of the more conventional fuels. Levels of NO_x associated with combustion of oil and gas may also reflect the more complete combustion of organics.[7]

The recent rapid increase in the use of wood for heating has caused the price of firewood to rise in many areas of the country, while its availability has decreased. Funded by the U.S. Department of Energy (DOE) Appropriate Technology small grants program, ETS, Inc., of Roanoke, Virginia, has designed and constructed a fluidized bed home heating unit which is fired on wood chips instead of cordwood usually used in woodstoves. The purpose for the development of this device is threefold. First, by increasing combustion efficiency, the fluidized bed device could significantly reduce air pollution from wood combustion. Second, the use of wood chips enables the design and construction of automated fuel handling facilities, greatly increasing the potential convenience of heating with wood over the use of cordwood in fireplaces or woodstoves. Finally, wood chips are a cheaper fuel than cordwood and promise more efficient use of timber resources, because the whole tree, rather than just the main woody portions, can be chipped and utilized as fuel.

The purpose of this study is to measure the emissions from this fluid bed residential wood chip combustor, and to compare these emissions with those from a residential woodstove and those from industrial wood-fired boilers. Emission comparisons will be made using data from two other RTI studies of emissions from woodstoves and emissions from industrial wood combustors.[22,23] Because the analyses for both of these studies were done in-house at RTI, the validity of these comparisons should be especially good.

2.0 EQUIPMENT AND FUEL

Figure 1 shows schematically the key features of the tested home heating system, which utilizes the fluid bed principle. The system consists of five basic components:

1. Wood feed conveyor.

2. Fluidized bed furnace with a 14-inch diameter bed, a gas/water heat exchanger and a forced draft fan.

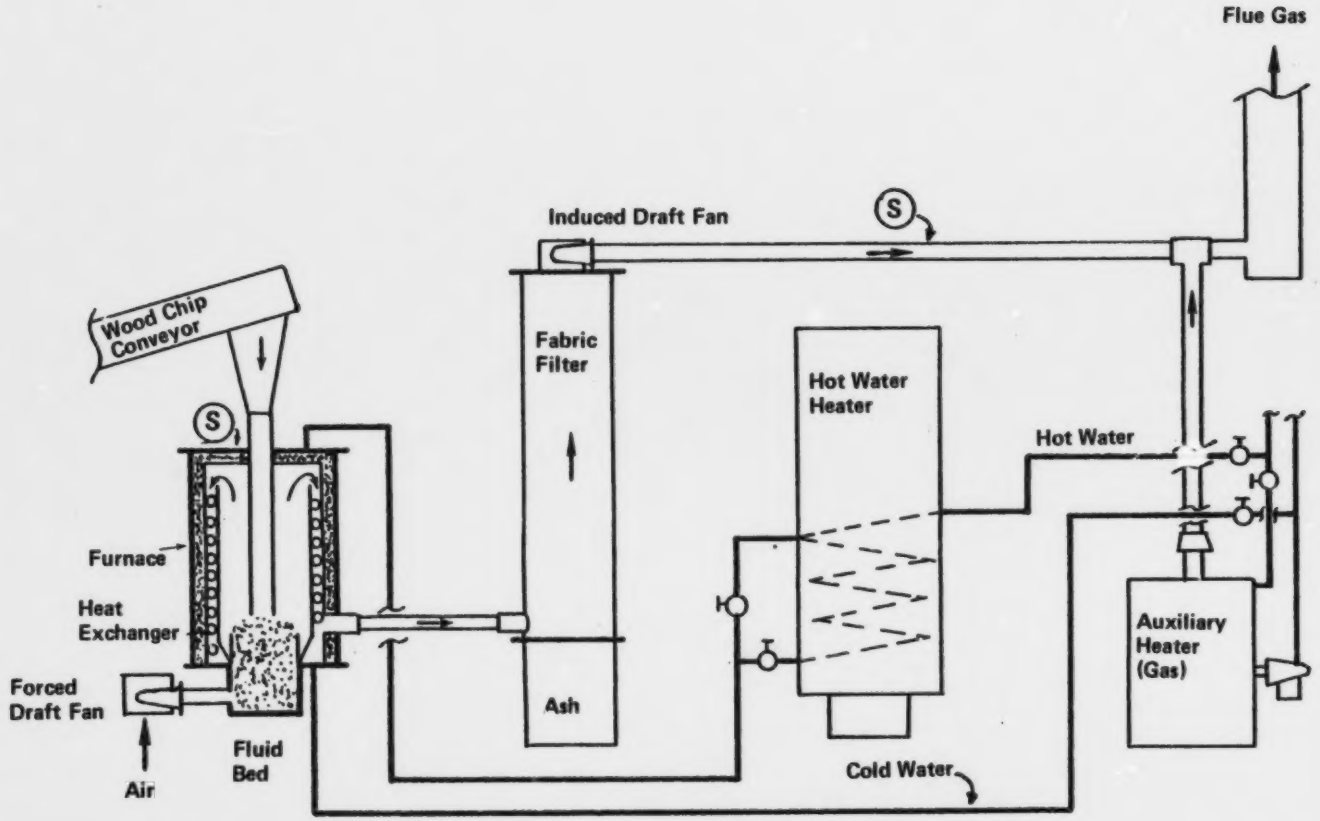
3. A fabric filter using a 5-inch diameter, inside-out flow, shaker cleaned filter bag, removable ash container, and induced draft fan.

4. A hot water heater to supply domestic hot water to the house. The water is heated by both a gas-fired and a wrap-around heat exchanger using the hot water output of the fluidized bed furnace. Valves are provided to bypass the hot water heat exchanger.

5. An auxiliary heater for supplying space heat to the house when the wood system is not operating. The auxiliary heater incorporates a circulating water pump. Valves are provided to include or bypass the fluidized bed exchanger.

More complete description of this fluidized bed combustion system may be found in the final report on "The Fluidized Bed Home Heating Furnace" by ETS, Inc., which is included as Appendix A. The advantage of this system is that by using small pieces of wood (i.e., wood chips) the flow rate of wood can be controlled, thus permitting a combustion process having a controlled excess of oxygen, resulting in both maximum recovery of the wood heating value and reduced emissions.

The fluid bed is a relatively new approach to the design of combustors. The fluidized bed is formed by flowing air up through a bed of inert particles. The air velocity through the bed, and hence, the pressure drop must be greater than the value required to support the bed weight, but less than the value required to sweep the particles out of the bed. The dynamic condition of a fluidized bed is quite analogous to that of a boiling liquid.



Note: S indicates sampling points.

Figure 1. Fluidized bed home heating system schematic.

The function of the fluidized inert material is to heat the incoming solid fuel to ignition temperature, and to maintain residence time sufficient for combustion of all burnable solid particles within the combustor.

In addition to the fluidized bed mode, the furnace was also modified for combustion in a cyclone mode. During the fluid bed mode, wood was fed in through a tube in the center of the bed and dropped on the fluid bed where combustion took place. In the cyclone mode, wood was fed in through a forced draft fan and blown into the cyclone burner where it was combusted.

Fuel used in these tests was chipped pine; the chips were approximately 1/4- to 1/2-inch in length. Measured and calculated fuel characteristics are presented in Table 1.

Temperatures during testing were monitored in the bed, above the bed, and in the stack at the point of sampling. Stack flow rates were measured using a Pitot tube immediately prior to the sampling point. A more complete discussion and description of parameters measured during each test may be found in Appendix A.

TABLE 1. FUEL CHARACTERISTICS

Moisture Content
FB-1 = 11.7% FB-2 = 10.9% FB-3 = 10.9% Average Moisture = 11.2%
Density Measured
0.24 g/mL = 15 lb/ft^3
Heating Value
Dry, average value = 8,500 Btu/lb
Heating value corrected for 11.2% moisture = 7,445 Btu/lb
Volume heating value = 111,700 Btu/ft^3

3.0 SAMPLING PROCEDURES--ORGANICS

A whole test integrated sample of polycyclic organic matter and other organic emissions was collected by a modified Method 5 sampling train similar to the one described in the residential wood combustion trial protocol.[24] The RTI sampling train was of all-glass/Teflon construction which consisted of the following: a glass probe, a heated filter box (>204° C) containing a fiberglass filter, a series of condensers, a water-cooled XAD-2 resin chamber, a series of ice-cooled impingers, a drying cartridge filled with silica gel, and a suitable air moving and air monitoring device. The basic method and equipment were selected in accordance with the protocol; however, the physical arrangement of the site and problems which arose during the testing necessitated some departure from the basic protocol.

The main departure was in the use of a series of two condensers and a condensate trap located between the filter box and resin chamber. This section was configured in the following manner: a 90° ground glass joint brought the gas flow out of the filter box and into an Allihn condenser (300 mm). The gas then flowed through a 180° ground glass joint; the bottom of which was tapped to provide a connection for a 250 mL amber condensate flask. The gas was further cooled by being passed through a Graham condenser (250 mm) prior to entry into the XAD resin chamber. (Any condensate was trapped ahead of the XAD.) This reduced the possibility of flushing of the XAD with large quantities of water and possible channelling in the XAD bed.

Other changes to the protocol included the use of an all-glass probe and the elimination of the particulate filter between the silica gel impinger and the dry impinger of the system. This filter was eliminated because low flow conditions and low particulate and organic loadings obviated its need. Organic breakthrough in the XAD module was not encountered during any of the tests. In addition, the impinger solutions were colorless and odorless in

all tests. Thus, no significant organics penetrated the system past the XAD module, confirming that the final filter was unnecessary. The impinger system consisted of four impingers mounted in series. The first two impingers were each filled with 100 mL of water. The second impinger was a modified Nuburg. The third impinger was dry, and the fourth contained 300 to 400 g of silica gel.

Altogether the system consisted of five subsections (see Table 2). These subsections were acid cleaned in the laboratory, and washed with methylene chloride in the laboratory and prior to their assembly at the testing site. The joints were taped with Teflon and clamped to facilitate the leak test.

The sampling train was set up on a platform near the fluidized bed combustion unit. A 3-inch flue was used to exhaust gas from the baghouse outlet. A tee was placed in this flue to allow a good point for sampling. The flue gas flow was diverted 90° at the tee; the other side of the tee was butted off and a port was drilled to allow insertion of a straight glass probe parallel to and directed straight into the gas stream. The glass probe was inserted in the flue in accordance with the standard Method 5 protocol leaving 8 duct diameters ahead of the probe free of obstructions and two behind it before the tee connection. Assembly and checkout were conducted according to a test protocol developed to meet the test situation, as well as to incorporate the trial protocol. The filter box was heated to 205° C, the resin trap was cooled to less than 20° C, and the system was leak checked per standard procedures. Taping of the joints facilitated the leak testing and reduced the time that would have been spent in chasing down leaks. All the necessary cooling lines were connected to the condensers and the XAD column. The cooling water was provided by an ice chest with ice and water. The system was wrapped with insulating materials to protect it from sunlight and to maintain coolness.

Operation of the sampling equipment consisted primarily of maintaining the flow of the coolant, monitoring all temperatures, gas flow rates, and making the necessary adjustments. Backup filters and glassware were cleaned and at hand and could be rapidly installed with a minimum of downtime.

TABLE 2. SAMPLE SYSTEM

Section 1. Probe Section

A. All glass probe
B. Flexible Teflon connector
C. Ground glass joint (female)
D. Electrical heating tape, thermocouple, controller

Section 2. Particulate Filter

A. Ground glass joint (male)
B. Glass filter holder (2 halves jointed with Bezel ring)
C. Sintered glass filter support with sealing gasket
D. Glass fiber filter
E. Heated box, thermocouple, and remote controller

Section 3. Condenser Section

A. 1-300 mm Allihn condenser
B. 1-250 mm Liebig condenser
C. 2-90° ground glass T/S joint
D. 1-250 mL infrared shielded flask
E. 1-180° ground glass joint with condensate tap
F. Coolant system

Section 4. XAD Resin Column

A. Jacket resin column with sintered glass plug (interior 2" wide, 50 g capacity)
B. XAD resin
C. Spring loaded perforated end plate

Section 5. Impinger

A. Four impingers
   1st, 100 mL water
   2nd, modified Nuburg with 100 mL water
   3rd, empty
   4th, silica gel (200-300 g)
B. Water bath cooled with ice water and portable condenser
C. Gas moving and monitoring attachment

Mass emissions were collected over a 77 to 166 minute interval depending on the volume of sample required for analysis and how long the system could be run before the filter clogged. At the conclusion of the sampling run, the train was shut down, disassembled, and sample recovery was performed on site. Samples taken included probe wash, filter particulate, condensate, and impinger water. The XAD module was capped off and transported back to the laboratory in a cool, dark container for sample recovery. All samples were stored in amber glass bottles under refrigeration prior to analyses.

4.0 ANALYTICAL PROCEDURES

4.1 GAS ANALYSIS

Stack gas was continuously monitored for nitrogen oxide (NO_x) content during the test using a photoluminescent detector manufactured by Thermo Electron Corporation. A separate 1/2-inch stainless steel probe was used to sample the flue gas for gas composition analysis. The probe was packed with glass wool and a water cooled condenser was placed in the sample line to prevent the fouling of the instrument. In addition to the NO_x analysis, discrete glass bulb samples of the flue gas were taken during each test. These glass bulb samples were returned to the laboratory for analysis by gas chromatography for carbon monoxide.

4.2 ORGANIC ANALYSIS

4.2.1 Sample Preparation

Modified Method 5 samples which were analyzed for organics include: probe wash (CH_2Cl_2) filter, condenser and XAD module wash (CH_2Cl_2), XAD-2 adsorbent, condensate catch, and impinger water. The probe wash was filtered to remove particulates captured by the probe during sampling. These particulates were weighed, and their weight was added to the weight of particulate caught on the Method 5 filter to give total particulate sampled during the test. The sampling train filter was then placed in a glass soxhlet thimble along with the probe wash filters and the XAD-2 adsorbent. The filtered probe wash and the condenser/XAD-2 module wash were poured into the soxhlet flask along with enough fresh CH_2Cl_2 to bring the volume to 500 to 700 cc. The soxhlet apparatus was then covered with foil and allowed to reflux for 24 hours. Following extraction, the filtrate was placed into a Kuderna-Danish evaporator and concentrated to 10 to 25 cc. The resulting concentrate was stored at 4° C until analysis.

The aqueous portion in the sampling train, impingers, and condensates were added together and extracted with a separatory funnel at pH of 2.0 ± 0.5 and 12.0 ± 0.5 as described elsewhere.[24] Two extractions were done at each pH. The CH_2Cl_2 from each set of extractions was added together and concentrated to ~10 mL. The resulting sample was stored at 4° C until analysis.

4.2.2 Total Organics

Organic analyses were performed separately on the types of concentrated samples described in Section 4.2.1. Total organics with a boiling point of 100 to 300° C were determined by total chromatographable organics (TCO) and gravimetric analyses described elsewhere.[22] Chromatograms of a hydrocarbon standard that were obtained on the same day as sample chromatograms gave retention times corresponding to the boiling point range 100° to 300° C. Calculation of TCO in each sample was based on the integrated peak area between these retention times and the peak area and the concentration of an internal standard (triphenyl ethylene).

Organics with a boiling point above 300° C were determined by weighing 0.5 mL samples that were evaporated to dryness. A complete description of this technique can be found elsewhere.[24] Results from TCO and gravimetric analyses were totaled to give total organics for the sampling period.

4.2.3 PNA Analysis--Gas Chromatography

RTI has amassed considerable experience in the analysis of PAH in various process streams, including the aqueous condensate and tar effluents from coal gasification.[25 26 27] During these studies, RTI encountered difficulty in characterizing these highly complex mixtures by gas chromatography-mass spectroscopy (GC/MS) in a time- and cost-effective manner. This motivated the development of a direct technique for the analysis of PNAs in complex mixtures utilizing glass capillary gas chromatography (GC^2). This technique has been presented in detail in two papers,[25 26] and was used for PAH quantitation in this study.

Gas chromatographs of the sample extracts indicated that the samples obtained from the residential combustion unit were very complex. This complexity, in conjunction with project time and cost restraints, led to

the selection of GC[2] as the analytical method for determining PNA concentrations in the modified Method 5 sample extracts. A Varian 3700 GC[2] system with a flame ionization detector (FID) was used for these analyses. The system was all-glass from the injector to the detector. A wall-coated OV-101 capillary column was used in the system. All sample wetted parts were made of glass. Helium was used as the carrier gas as well as the makeup gas. Chromatographic conditions are listed in Table 3. Samples were injected using the Grob "splitless" technique,[28] and sample volumes ranging from 3 to 4 μL were used. The splitless technique consists of injecting the sample and then 30 seconds later, opening the splitter to remove the excess solvent. This prevents a long solvent tail. The advantages of using this technique for polycyclic materials are well documented.[29]

TABLE 3. CHROMATOGRAPHIC CONDITIONS

Instruments	Varian 3700 with "all glass" capillary systems
Detector	FID 280° C
Column	25 mm × 0.25 mm I.D. WCOT OV 101, Borosilicate capillary
Carrier	Helium, 16 psi
Temperature	50° C for 1 min, 4° C/min to 265° C, hold 20 min
Injection	Splitless, 1-min delay
Detector gas flows	Optimum (~1 mL/min)
Makeup gas	Helium (~29 mL/min through detector)

Prior to GC[2] injection, concentrated sample extracts were internally standardized. A problem was to find a suitable internal standard for GC analysis since the extracts were substantially complex. Triphenyl ethylene (TPE) was found to be the most suitable of the many internal standards tested since it was present at negligible concentrations in the extracts, was similar in nature to other aromatic compounds, and was well separated from the peaks of the compounds of interest.

PNA analyses were performed separately on the two samples described in Section 4.2.1. Aliquots were internally standardized with triphenyl ethylene. Retention times of chromatographic peaks from GC^2 analysis of these aliquots were compared to peak retention times from GC^2 analyses of a solution of 25 PNAs and TPE in order to identify the PNAs in question. Standard PNA solutions were run at regular intervals to assure that instrument retention times had not changed. Once PNA peaks were identified, compound quantitation was accomplished using the known concentration of TPE in the samples spiked with TPE only and response factors (RF) calculated from the standard composed of 25 PAHs and TPE at known concentrations. The standard was periodically run on the GC^2 to give response factors for each PAH. Response factors account for decreasing area counts for equally concentrated PAHs as the GC^2 approaches its limits for eluting high boiling point compounds and were determined from calibration curves.

5.0 EXPERIMENTAL

The fluidized bed home heating unit was operated during the test by ETS personnel. Details of the operating procedures may be found in the report contained in Appendix I. In general, the operation of the fluidized bed unit was satisfactory in all tests, and fairly constant conditions were achieved for each test. Forced draft fans and controls of wood feed rate enabled the operators to produce very reproducible conditions from test to test. Important operating parameters for the eight fluid bed and cyclone tests are given in Table 4. These eight tests consisted of four sets of duplicate tests, each set representing a change in equipment configuration or sampling technique. Tests FB-1 and FB-2 were duplicate tests in the fluid bed mode utilizing the baghouse for particulate control. Tests FB-3 and FB-4 were duplicate tests in the fluidized bed mode but without the baghouse for particulate control. Tests C-1 and C-2 were duplicate tests in the cyclone firing mode. Tests FB-5 and FB-6 were duplicate tests in the fluidized mode during which the sampling probe was inserted into the fluidized bed reactor and sampled gases just above the fluid bed. More complete operating data for these tests may be found in the appendix.

The efficiency values in Table 4 were calculated using Orsat CO values. Because of disagreement with CO data obtained from a second independent method (see Section 6.2), these data and the efficiency values are suspect. However, since the Orsat data are most likely too high if inaccurate, these efficiency values may be used as conservative estimates of these heating appliances' efficiency. These efficiency values are superior to those of conventional woodstoves, which are typically about 50 percent efficient.

TABLE 4. OPERATING PARAMETERS

Test	Test configuration	Temperature			Flue gas flow rate (scm/hr)	Fuel consumption (kg/hr)	Efficiency (%)
		Bed	Above bed	Stack			
FB-1	Fluid bed, with baghouse	827	840	40	56.49	4.46	66
FB-2	Fluid bed, with baghouse	858	874	71	36.75	3.03	77
FB-3	Fluid bed, without baghouse	865	873	72	60.45	3.52	72
FB-4	Fluid bed, without baghouse	894	648	77	54.37	4.36	62
FB-5	Fluid bed, sampled above bed	862	894	108	68.06	5.56	66
FB-6	Fluid bed, sampled above bed	935	846	106	71.73	5.29	66
C-1	Cyclone, without baghouse	933	686	84	47.49	3.71	69
C-2	Cyclone, without baghouse	972	759	87	42.24	3.60	75

6.0 RESULTS

In general, the residential wood chip combustor tested in this study was successful in reaching its goals of higher efficiency and lower emissions than conventional wood-fired heating appliances. Table 5 is a compilation of emission factors for particulate, nitrogen oxides, hydrocarbons, and carbon monoxide measured during the eight test runs of the wood chip combustor. Emissions of these pollutants will be discussed separately in the following sections and compared with emissions from a conventional residential woodstove and industrial wood-fired boilers. This will be followed by a discussion and emissions comparison for 25 polycylic aromatic hydrocarbon (PAH) compounds measured during these tests.

TABLE 5. EMISSION FACTORS (g/kg fuel consumed)

	Test							
Compounds	FB-1	FB-2	FB-3	FB-4	C-1	C-2	FB-5	FB-6
Particulate	0.03	0.04	3.08	1.94	1.04	2.01	28.07	15.04
NO_x	0.94	0.88	1.20	0.89	1.33	1.22	1.26	1.23
Hydrocarbons	0.91	1.57	1.72	1.48	0.11	0.02	0.28	0.95
CO (GC) (number of measurements)	11.1 (3)	51.6 (3)	42.9 (3)	14.0 (3)	0.5 (2)	2.9 (2)	8.3 (1)	16.9 (2)
CO (Orsat)	205.68	197.09	515.37	140.16	128.01	73.30	137.30	339.14

6.1 PARTICULATE EMISSIONS

Particulate emissions were measured using the standard Method 5 method. Examination of particulate emission factors for the eight test runs, (Table 5) leads to the following conclusions: Tests with the baghouse in place, FB-1

and FB-2, show that the baghouse is extremely effective in reducing particulate emissions from this heating device. Particulates from FB-1 and FB-2 are reduced by two orders of magnitude over uncontrolled particulate emissions from fluid bed tests, FB-3 and FB-4. Tests FB-5 and FB-6 have higher particulate levels because the probe was positioned just above the fluidized bed. These tests are not representative of actual particulate emissions.

Figure 2 is a comparison of particulate emissions from the fluid bed tests without the baghouse, the cyclone tests, tests from residential woodstove,[22] and industrial wood-fired boilers.[30] It may be seen in this figure that the emissions from the fluid bed and cyclone tests fall in between those from residential woodstoves and those from industrial wood-fired boilers. The forced air flow through this fluidized bed combustion unit and through the cyclone combustion unit apparently entrains more particulates into the flue gas than in a conventional woodstove, but not as many as are entrained in the flue gas of industrial wood-fired boilers. The cyclone firing mode reduces particulate emissions compared to the fluidized bed firing mode, probably reflecting a more complete combustion of the wood particles in the cyclone-fired burner. This more complete combustion is reflected in other emission factors to be discussed in the following sections.

6.2 CARBON MONOXIDE EMISSIONS

Carbon monoxide emissions were measured by discrete samples taken during the tests, using two different analytical techniques. Standard Orsat measurements of carbon monoxide were made by ETS testing personnel. Two Orsat measurements were made for each of the tests, FB-1 and FB-2. All other tests had single Orsat CO measurements. In addition to Orsat measurements, separate grab samples of flue gas were collected and transported back to the laboratories at RTI for carbon monoxide analysis using gas chromatography (GC). Three glass bulb samples were taken for fluidized bed runs FB-1 through FB-4. Airtight stainless steel canisters were used to sample flue gas for carbon monoxide for runs C-1, C-2, FB-5 and FB-6.

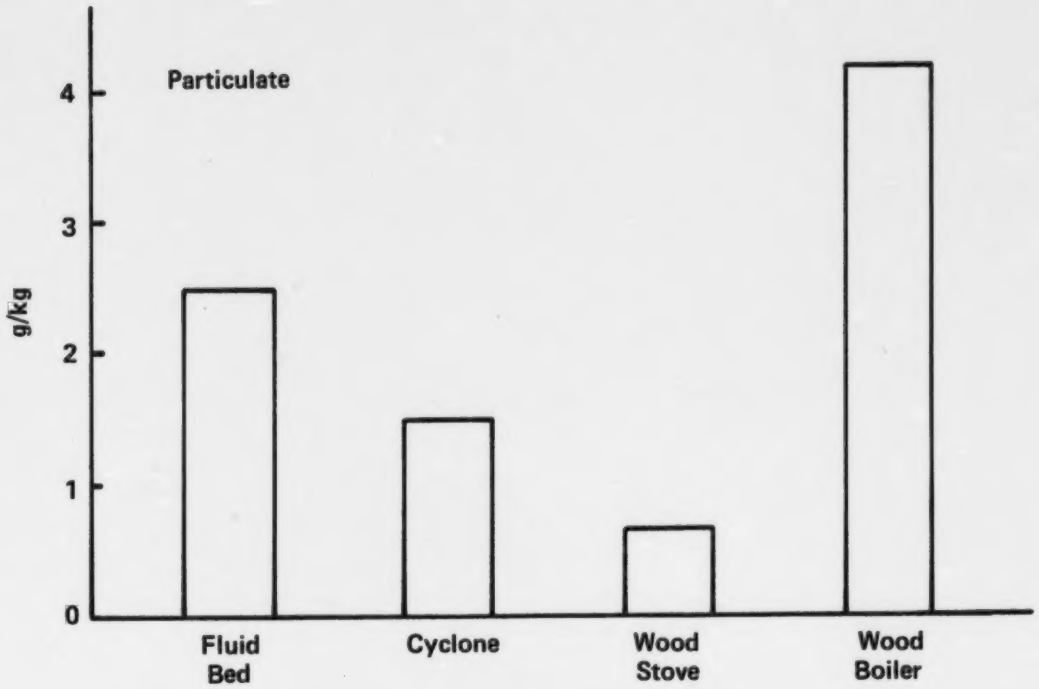


Figure 2. Comparison of particulate emission factors.

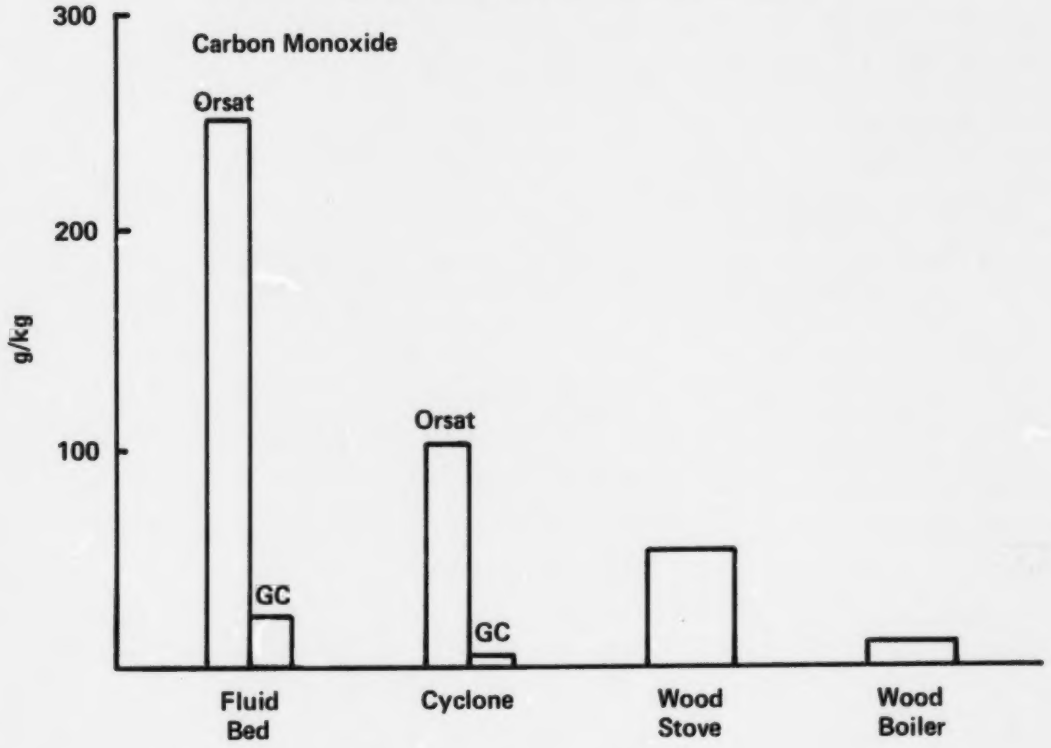


Figure 3. Comparison of carbon monoxide emission factors.

These samples were larger than the glass bulb samples and were taken over a longer period of time; therefore only two samples were taken for C-1, C-2 and FB-6, and one for FB-5.

Table 6 is a comparison of CO emission levels measured by Orsat and gas chromatography techniques. The values for each run in this table were obtained by averaging all analyses for each sampling and analysis method. As may be seen in Table 6, there is a serious discrepancy between Orsat CO measurements and gas chromatography CO measurements, with Orsat measurements over an order of magnitude higher in most cases. Because the CO samples for GC analysis were transported back to the laboratory and were held over the weekend prior to analysis, both sets of analyses are suspect. A more dependable continuous analysis system needs to be set up on this heating device to confirm or reject these values. In general, the Orsat values do seem to be too high, and do not show consistent variation with process conditions. The GC values do show such consistent variations, but appear to be a bit too low. However, with the increase of combustion efficiency that is implied, these may be valid concentrations.

TABLE 6. COMPARISON OF ORSAT AND GC CO MEASUREMENTS

	Test							
	FB-1	FB-2	FB-3	FB-4	C-1	C-2	FB-5	FB-6
Orsat								
%	1.3	1.3	2.4	0.9	0.8	0.5	0.9	2.0
g/hr	918	597	1,814	612	475	264	766	1,794
g/kg	206	197	515	140	128	73	138	339
GC								
%	0.07	0.34	0.20	0.09	0.003	0.02	0.05	0.10
g/hr	49.4	156.2	151.2	61.1	1.8	10.6	45.9	9.7
g/kg	11.1	51.6	42.9	14.0	0.5	2.9	8.3	16.96

Figure 3 is a comparison of average carbon monoxide emission factors for six fluidized bed test runs (Orsat and GC), the two cyclone runs (Orsat and GC), two woodstove tests,[22] and typical emissions from industrial wood-fired boilers.[30] Examination of this figure suggests that the Orsat

method CO measurements are too high. GC measurements of CO for the fluid bed and for the cyclone runs indicate that the former has slightly higher CO emissions than industrial wood-fired boilers, and the latter has lower CO emissions than industrial wood-fired boilers. Both combustion modes show lower emissions than woodstoves. This is an expected difference because of increased thermal efficiency and combustion efficiency in the fluid bed and cyclone devices. Again, the cyclone device appears to be more efficient at burning wood than the fluid bed device, as evidenced by CO emission levels.

6.3 NO_x EMISSIONS

Examination of Table 5 shows that NO_x emission factors for the fluid bed test and for the cyclone test are fairly low, with the cyclone test having slightly higher NO_x emissions on the average than the fluid bed test. Figure 4 is a comparison of average NO_x emission factors from the six fluid bed tests, the two cyclone tests, two woodstove tests,[22] and typical NO_x emissions from industrial boilers.[23 31] Examination of Figure 4 shows that, although NO_x emissions from the fluid bed combustor and the cyclone combustor are slightly higher than those measured from a conventional woodstove, they are within the range reported for industrial wood boilers (0.1-1.1 g/kg).[23 31] The fact that NO_x emissions were only slightly elevated for the fluid bed and cyclone tests indicates that good combustion control was achieved during these tests and that emissions from residential combustion of wood can be controlled by combustion modification without significantly increasing the NO_x emission levels.

6.4 HYDROCARBON EMISSIONS

Examination of Table 5 shows hydrocarbon emission factors for the fluid bed test run and the cyclone test run, and it shows that the cyclone-firing mode was much more efficient in reducing total hydrocarbon emission than the fluidized bed combustion mode. This is probably due to more efficient air-fuel mixing in the cyclone combustion mode than in the fluidized bed mode. During fluidized bed combustion, wood chips are dropped on the surface of the fluid bed where combustion apparently takes place. This

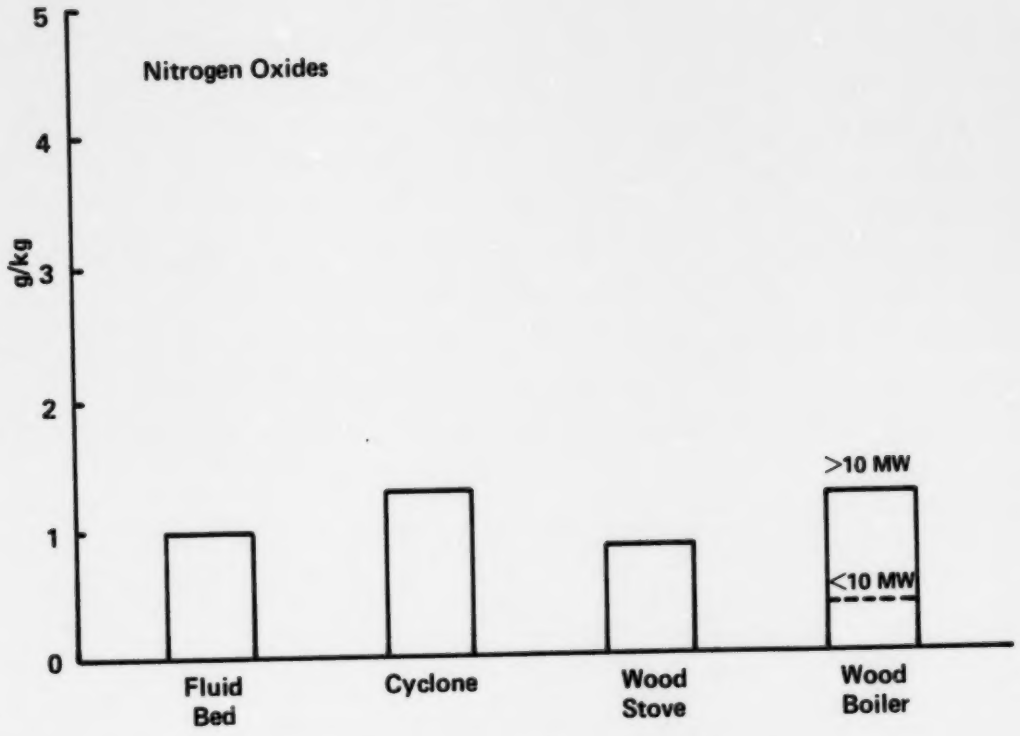


Figure 4. Comparison of NO_x emission factors.

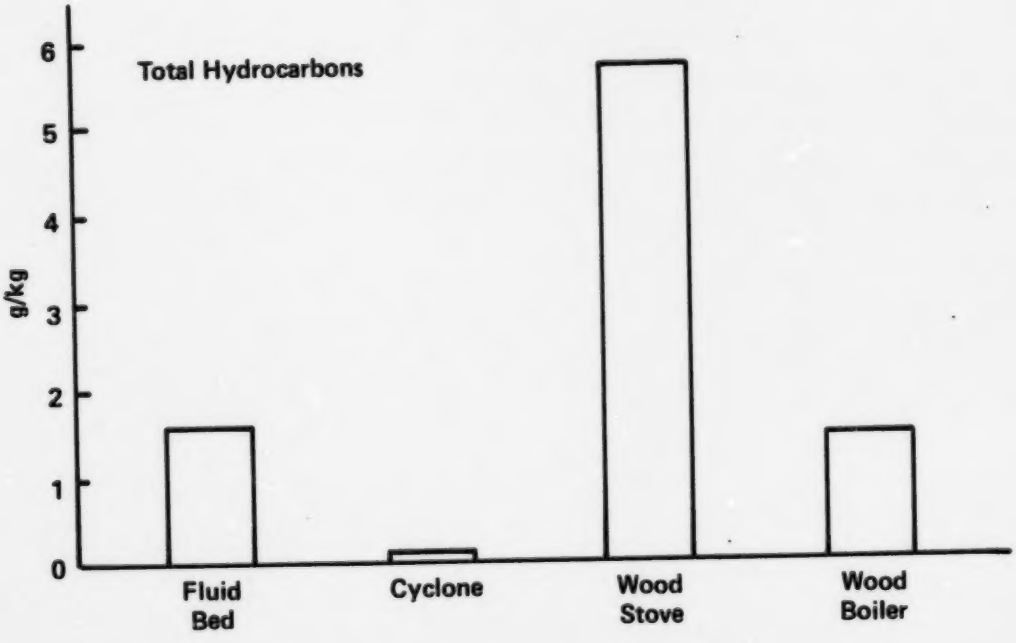


Figure 5. Comparison of total hydrocarbon emission factors.

combustion was not complete, as evidenced by the baghouse runs during which the baghouse particulate was observed to have considerable amounts of partially combusted wood particles in the form of carbon particles. Injection of the wood particles into the fluid bed, rather than on top of the bed may result in lower hydrocarbon emissions for the fluid bed runs. This modification should be investigated with later tests.

Figure 5 is a comparison of averaged total hydrocarbon emission factors for the fluid bed test and the cyclone test and also from two woodstove tests,[28] and industrial wood-fired boilers.[30] It may be seen in this figure that both the fluidized bed combustion and the cyclone combustion mode were extremely effective in reducing total hydrocarbon emission levels over those measured from conventional woodstoves. The fluid bed test achieved hydrocarbon emission factors very similar to those of industrial wood-fired boilers. Cyclone tests showed even more efficient reduction of hydrocarbon emissions, with hydrocarbon emission factors being only a fraction of those measured in fluidized bed tests or in the industrial wood-fired boilers. This is in line with the lower carbon monoxide levels, lower particulate levels, and higher NO_x levels measured during the cyclone test.

6.5 PAH EMISSIONS

Table 7 is a compilation of emission factors for PAH compounds for the fluid bed test and for the cyclone test. Several interesting points may be observed from this table. Comparison of the PAH emission factors from the test with baghouses (FB-2 and FB-2), and the tests without baghouses (FB-3 and FB-4) show that although emission factors for the lighter PAH compounds are similar for these four runs, emission factors for the heavier PAH compounds (which include the compounds of most environmental concern, such as benzo(a)pyrene) are reduced in the fluid bed test with the baghouse compared to the fluid bed test without the baghouse. Two explanations are presented to account for this reduction. First, and probably most important, as the flue gas cooled in the water tube heat exchanger, heavier organic compounds such as BaP condensed from the flue gas stream and was adsorbed by the flue gas particulate. Removal of this particulate from the flue gas would thus reduce BaP emissions as well. Second, much of the particulate collected in

TABLE 7. EMISSION FACTORS, PAH COMPOUNDS (mg/kg fuel consumed)

Compound	Test							
	FB-1	FB-2	FB-3	FB-4	C-1	C-2	FB-5	FB-6
Naphthalene	34.40	50.06	43.13	36.09	0.91	5.49	43.43	323.00
Biphenyl	2.93	8.96	12.17	8.63	0.39	0.12	0.80	13.89
Fluorene	9.79	21.54	22.83	21.47	0.18	0.23	1.31	13.14
Phenanthrene Anthracene	44.36 9.45	17.81	30.80 31.54	52.99 21.51	3.43 0.09	1.00	5.88 0.39	49.04 2.35
Carbazole	0.13	ND	0.38	0.32	0.02	ND	0.005	ND
1-Methylphenanthrene	5.08	12.36	17.82	4.99	0.38	0.71	1.85	8.16
9-Methylanthracene	0.33	0.37	0.55	0.28	ND	0.06	ND	ND
Fluoranthene	25.38	17.11	27.10	53.05	0.89	0.68	3.08	18.11
Pyrene	17.53	18.74	39.05	56.77	1.35	0.57	3.86	21.51
Benzo(a)anthracene Chrysene	2.74 2.05	0.76 0.48	7.83 4.97	15.60 8.67	0.28 0.04	0.05	ND ND	ND ND
12-Methylbenz(a)anthracene	0.02	0.07	0.02	0.62	ND	0.03	ND	0.06
7-Methylbenz(a)anthracene	0.20	ND	0.27	0.34	ND	0.02	0.03	0.30
7,12-Dimethylbenz(a)-anthracene	ND	ND	ND	ND	ND	ND	ND	ND
Benzo(b,k)fluoranthene	0.09	ND	9.94	21.33	ND	ND	ND	ND
Benzo(e)pyrene Benzo(a)pyrene	0.20 0.44	ND 0.05	5.87 10.70	11.34 25.59	ND ND	ND ND	0.05 0.32	0.90
Perylene	0.03	0.02	0.81	1.32	ND	ND	0.63	0.69
3-Methylcholanthene	ND	ND	ND	ND	ND	ND	ND	ND
Indeno(1,2,3-cd)pyrene	ND	ND	ND	0.61	ND	ND	ND	ND
Dibenz(a,h)anthracene	ND	ND	ND	ND	ND	ND	ND	ND
Benzo(g,h,i)perylene	ND	ND	ND	ND	ND	ND	ND	ND
<Detection Limit	0.004	0.005	0.007	0.005	0.002	0.003	0.005	0.026

ND = Not detected.

the bag was a carbon char from partially combusted wood particles. It is possible that this charcoal material may act as a filter adsorbant, adsorbing heavier PAH compounds still in the vapor phase at the filter bag. Extraction of the baghouse particulate, using methylene chloride, and analysis for PAH compounds (Table 8) confirms this hypothesis that the baghouse particulate has indeed adsorbed significant quantities of PAH compounds and is especially enriched in the heavier PAH compounds such as benzo(a)pyrene. Thus, charcoal coated baghouse filters appear to be an effective means of reducing PAH emissions from residential wood combustion units.

Two fluidized bed tests, FB-5 and FB-6, were sampled with the probe actually extending down into the combustion zone of the fluidized bed unit. Comparing the PAH emission factors for these tests with those from FB-3 and FB-4, (the fluid bed tests without the baghouse) shows that, compared to FB-3 and FB-4, PAH emission factors for tests FB-5 and FB-6 were significantly lower for heavier PAH compounds. Since the sampling point for FB-5 and FB-6 was a few inches above the fluid bed, the low levels of heavy PAHs sampled during these tests imply that significant formation of the heavier PAH compounds is occurring in the upper portion of the furnace chamber or in the water tube heat exchangers. The cyclone tests, however, show no appreciable formation of heavy PAH compounds in this zone. Low hydrocarbon emission factors for the cyclone tests suggest that the small amount of organic material in the flue gas from these tests minimized any significant PAH formation. With respect to PAH emission factors, the cyclone combustor again appears to be superior to the fluid bed combustor in reducing these emissions.

Table 9 gives PAH emission factors for woodstove and industrial wood-fired boilers. Like the analyses for this study, the analyses from which these emission factors were derived were performed in-house at RTI. Comparing these emission factors in Table 9 with those in Table 7 from the fluidized bed and cyclone combustor tests, one may see that the fluidized bed tests, without baghouse in place (FB-3 and FB-4), had similar emission factors as the woodstove for the lighter PAHs, yet higher emission factors for the heavier PAHs than for the woodstove tests. These high emission factors are in spite of significantly lower total hydrocarbon emission

TABLE 8. PAHs IN BAGHOUSE PARTICULATE

Compound	µg/g
Naphthalene	150.31
Biphenyl	6.71
Fluorene	21.20
Phenanthrene	232.58
Anthracene	70.07
Carbazole	1.24
1-Methylphenanthrene	11.35
9-Methylanthracene	3.13
Fluoranthene	394.94
Pyrene	439.54
Benzo(a)anthracene	424.98
Chrysene	204.35
12-Methylbenz(a)anthracene	23.66
7-Methylbenz(a)anthracene	13.22
7,12-Dimethylbenz(a)anthracene	ND
Benzo(b,k)fluoranthene	718.28
Benzo(e)pyrene	742.02
Benzo(a)pyrene	895.29
Perylene	56.36
3-Methylcholanthene	ND
Indeno(1,2,3-cd)pyrene	67.75
Dibenz(a,h)anthracene	466.05
Benzo(g,h,i)perylene	ND

TABLE 9. PAH EMISSION FACTORS FOR WOODSTOVE AND INDUSTRIAL WOOD-FIRED (mg/kg)

Compound	Woodstove*	Wood boilers†
Naphthalene	36.74	1.31
Biphenyl	11.39	-
Fluorene	4.67	0.05
Phenanthrene	9.76	0.11
Anthracene	6.04	0.064
Carbazole	ND	0.0004
1-Methylphenanthrene	14.68	0.0027
9-Methylanthracene	2.21	0.0033
Fluoranthene	3.67	0.0073
Pyrene	2.62	0.025
Benzo(a)anthracene	0.08	0.026
Chrysene	1.58	0.008
12-Methylbenz(a)anthracene	0.07	-
7-Methylbenz(a)anthracene	0.50	-
7,12-Dimethylbenz(a)anthracene	ND	ND
Benzo(b,k)fluoranthene	1.46	0.010
Benzo(e)pyrene	0.55	0.008
Benzo(a)pyrene	0.63	0.007
Perylene	0.83	ND
3-Methylcholanthene	ND	ND
Indeno(1,2,3-cd)pyrene	ND	0.002
Dibenz(a,h)anthracene	ND	0.002
Benzo(g,h,i)perylene	0.03	0.006

*Average of two tests, oak logs.[22]

†Average of 21 tests on seven boilers.[23]

factors for the fluidized bed tests as compared to the woodstove tests (see Figure 5). This implies that PAH forming reactions are occurring during fluidized bed combustion in the residential wood chip burner, resulting in a larger portion of the total hydrocarbons in the flue gas being converted to PAH compounds. As mentioned before, the results of tests FB-5 and FB-6 suggest that these reactions occur above the bed, and perhaps in the water tube heat exchangers surrounding the furnace.

On the other hand, the cyclone tests, C-1 and C-2 show significantly reduced PAH emission factors compared to those for the woodstove (Table 9). In fact, PAH emission factors for the cyclone tests are almost as low as those measured on wood-fired industrial boilers. It appears that the very low level of total hydrocarbon observed in the flue gas from the cyclone tests (Figure 5) minimized the formation of the significant amounts of PAH compounds.

In conclusion, the emissions from the residential fluidized bed combustion unit were significantly reduced with respect to particulate, total hydrocarbons, and perhaps carbon monoxide. PAH emission factors were similar to those of woodstoves for lighter PAH compounds and higher by approximately an order of magnitude for the heavier PAH compounds. Thus, significant PAH formation is occurring in the fluidized bed above the fluid bed. The use of a filter bag for particulate control was found to reduce the emissions of heavier PAH compounds for the fluidized bed tests. Except for NO_x, the cyclone tests showed significant reductions in all emissions measured, over those from a residential woodstove, and were also lower than emissions measured during the fluidized bed combustion tests. PAH levels from the cyclone combustors were almost as low as those measured in industrial wood-fired boilers. The cyclone-firing mode thus appears to be superior to the fluidized bed-firing mode as presently designed in reducing emissions from the combustion of wood in residential home heating units. However, it is possible that, by introducing the wood chips into the fluid bed rather than on top of it, more complete combustion and hence lower emissions can be achieved in the fluid bed mode.

7.0 CONCLUSIONS

1. Both the fluidized bed combustion unit and the cyclone-fired combustion unit produced lower emissions of particulate, total hydrocarbons, and perhaps carbon monoxide, than emissions from a conventional residential woodstove.

2. Polycyclic aromatic hydrocarbon (PAH) emission factors for the cyclone-fired combustion tests were significantly lower than emission factors for PAHs from conventional woodstoves. However, PAH emission factors for the fluidized bed combustion tests were similar to those from woodstoves for the lighter PAH compounds, and were higher than residential woodstoves for the heavier PAH compounds. Lower total hydrocarbon emission factors for fluidized bed combustion tests, as compared to those for woodstoves, imply that a larger fraction of the total hydrocarbons from fluidized bed combustor are being converted to PAH compounds.

3. The baghouse installed on this fluidized bed combustion unit proved extremely effective in reducing total suspended particulate emissions from the combustion unit. In addition, collection of partially burnt carbonaceous wood particles in the baghouse resulted in significantly lower emission factors for heavier PAHs during the fluidized bed combustion tests.

4. Hydrocarbon emission sampling just above the bed for the fluidized bed combustion mode indicates that most of the significant formation of heavier PAH compounds is occurring above the bed at the inlet of the water tube heat exchanger or in the water tube heat exchanger itself.

5. Overall the cyclone combustor is superior to the fluid bed combustor in reducing all emissions except for NO_x. NO_x emissions are only slightly higher for the cyclone combustor than for the fluidized bed combustor. From an emission standpoint therefore, the cyclone-fired wood chip combustor appears to be superior to the fluidized bed wood chip combustor. This is especially true with respect to PAH emission factors, with the cyclone combustor emission factors for PAH compounds being almost as low as those measured from industrial wood-fired boilers.

REFERENCES

1. Trefil, J. Sawing Away at OPEC. Science 80, Vol. 1, No. 5, 1980. pp. 16-18.

2. Cooper, J. A. and J. G. Watson. Portland Aerosol Characterization Study. Oregon Department of Environmental Quality, 1979.

3. Sanborn, Cedric, R., Richard L. Poirot, Gregory A. Heil, and Michael A. Blanchet. Preliminary Analysis of the Ambient Impacts of Residential Woodburning in Waterbury, Vermont. In: Proceedings of the Wood Heating Seminar, February 21-24, 1981, New Orleans, LA. Wood Heating Alliance, 1981. pp. 231-241.

4. Imhoff, Robert E., Justice A. Manning, William M. Cook, and Timothy L. Hayes. Preliminary Report on a Study of the Ambient Impact of Residential Wood Combustion in Petersville, Alabama. In: Residential Solid Fuels--Impacts and Solutions. John A. Cooper and Dorothy Maleck, eds. Oregon Graduate Center, 1982. pp. 520-538.

5. Carlson, James. H. Residential Wood Combustion in Missoula, Montana: An Overview of Its Air Pollution Contributions, Health Effects, and Proposed Regulatory Solutions. In: Residential Solid Fuels--Impacts and Solutions. John A. Cooper and Dorothy Maleck, eds. Oregon Graduate Center, 1982. pp. 539-550.

6. DeCesar, Richard T. The Quantitative Impact of Residential Wood Combustion and Other Vegetative Burning Sources on the Air Quality in Medford, Oregon. In: Residential Solid Fuels-Impacts and Solutions. John A. Cooper and Dorothy Maleck, eds. Oregon Graduate Center, 1982. pp. 551-565.

7. DeAngelis, D. G., D. S. Ruffin, J. A. Peters, and R. B. Reznik. Source Assessment: Residential Combustion of Wood. Prepared by Monsanto Research Corporation for EPA, EPA-600/2-80-0426, March 1980.

8. Milliken, John O. Airborne Emissions from Wood Combustion. Presented at the Wood Energy Institute, Wood Heating Seminar IV, Portland, Oregon, March 22-24, 1979.

9. United States Department of Energy. Health Effects of Residential Wood Combustion: Survey of Knowledge and Research, DOE/EV-0114, September 1980.

10. Butcher, Samuel S. and Michael J. Ellenbecker. Particulate Emission Factors for Small Wood and Coal Stoves. In: Residential Solid Fuels--Impacts and Solutions. John A. Cooper and Dorothy Maleck, eds. Oregon Graduate Center, 1982.

11. Cooke, Marcus W., John M. Allen, and Robert E. Hall. Characterization of Emissions from Residential Wood Combustion Sources. In: Residential Solid Fuels--Impacts and Solutions. John A. Cooper and Dorothy Maleck, eds. Oregon Graduate Center, 1982. pp. 134-163.

12. Barnett, Stockton G., and Damian Shea. Effects of Woodstove Design and Operation on Condensable Particulate Emissions. In: Residential Solid Fuels-Impacts and Solutions. John A. Cooper and Dorothy Maleck, eds. Oregon Graduate Center, 1982. pp. 227-266.

13. Milliken, John O. Airborne Emissions from Wood Combustion. Presented at the Wood Energy Institute, Wood Heating Seminar IV, Portland, Oregon, March 22-24, 1979.

14. Dipple, Anthony. Polynuclear Aromatic Carcinogens. In: Chemical Carcinogens. Charles F. Searle, ed. ACS, Washington, DC, 1976. pp. 245-314.

15. Peters, James A. POM Emissions from Residential Woodburning: An Environmental Assessment. In: Residential Solid Fuels--Impacts and Solutions. John A. Cooper and Dorothy Maleck, eds. Oregon Graduate Center, 1982. pp. 267-288.

16. Murphy, Dennis J., Roy M. Buchan, and Douglas G. Fox. Ambient Particulate and Benzo(a)pyrene Concentrations from Residential Wood Combustion in a Mountain Resort Community. In: Residential Solid Fuels--Impacts and Solutions. John A. Cooper and Dorothy Maleck, eds. Oregon Graduate Center, 1982. pp. 495-505.

17. Moschandreas, D. J., J. Zabransky, Jr., and H. E. Rector. Residential Indoor Air Quality and Wood Combustion. In: Proceedings of the Wood Heating Seminar, February 22-24, 1981, New Orleans, LA. Wood Heating Alliance, 1981.

18. National Institute for Occupational Safety and Health. Criteria for a Recommended Standard for Occupational Exposure to CO. Available from National Technical Information Service, PB 212 629, 1972.

19. Wainwright, P. Wood Energy, the North Carolina Effort. In: Proceedings of Wood Heating Seminars 1980/1981. Wood Heating Alliance, 1981.

20. National Institute for Occupational Safety and Health. Criteria for a Recommended Standard for Occupational Exposure to Oxides of Nitrogen (Nitrogen Dioxide and Nitric Oxide). U.S. Department of Health, Education, and Welfare. NIOSH 76-149, March 1976.

21. U.S. Environmental Protection Agency. Air Quality Criteria for Oxides of Nitrogen. Environmental Criteria and Assessment Office. Research Triangle Park, NC, Draft 1981.

22. Truesdale, R. S., K. L. Mack, J. B. White, K. E. Leese, and J. G. Cleland. Final Report: Characterization of Emissions from the Combustion of Wood and Alternative Fuels in a Residential Woodstove. RTI/1914-39-01F. EPA Contract No. 68-02-3170. March 1982.

23. Wainwright, P. B., M. Y. Aldridge, and R. S. Truesdale. A POM Emissions Study for Industrial Wood-Fired Boilers. North Carolina Department of Natural Resources and Community Development. April 1982.

24. Cooke, M., and J. M. Allen. Final Report on Trial Protocol for Sampling and Analysis of Emissions from Residential Wood Combustion Prepared for Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency, Contract No. 68-02-2686. 1981.

25. Gangwal, S. K., and D. G. Nichols. Chemical Characterization of Tar from Fixed-Bed Gasification of Eastern and Western Coals. Proceedings of the 20th Hanford Life Sciences Symposium, Richland, WA, October 1980.

26. Gangwal, S. K., et al. Pollutants from Synthetic Fuels Production: Sampling and Analysis Methods for Coal Gasification. U.S. Environmental Protection Agency, EPA-600/7-79-201. 1979.

27. Gangwal, S. K., et al. Evaluation of Relative Environmental Hazards from a Coal Gasifier. U.S. Environmental Protection Agency, EPA-600/S7-81-100. National Technical Information Service PB-81-221-301, Springfield, VA, 1981.

28. Grob, K., and G. Grob. Splitless Injection in Glass Capillary Gas Chromatography. J. Chromatogr. Sc., Vol. 7, 1969. p. 584.

29. Lee, M. L., and B. W. Wright. Capillary Column Chromatography of Polycyclic Aromatic Compounds: A Review. J. Chromatogr. Sc., Vol. 18, 1980. pp. 345-358.

30. Lim, K. J. Control of Gaseous Emissions from Industrial Wood Combustion. ASME-APCA-NCSU Wood-Fired Industrial Boilers Workshop, Raleigh, NC. April 1982.

31. Nunn, A. B. NO_x Emission Factors for Wood-Fired Boilers. EPA-600/7-79-219, U.S. Environmental Protection Agency, Washington, D.C., 1979.

Appendix A

FINAL REPORT

"FLUIDIZED BED HOME HEATING FURNACE"

DOE, Appropriate Technology Small Grants Program

#81-VA-0073-P-36,919

By:

ETS, INC.
Suite C-103, 3140 Chaparral Drive, SW
Roanoke, VA 24018

September 1982

Appendix A

TABLE OF CONTENTS

	PAGE (A-)
INTRODUCTION	3
WHY WOOD CHIPS?	3
THE FLUIDIZED BED HOME HEATING SYSTEM	5
TESTING PROGRAM	6
TESTING RESULTS	8
CONCLUSIONS	8
TABLE I - AVERAGED TEST DATA	9
TABLE II - CALCULATED DATA	10
TABLE III - FUEL CHARACTERISTICS	11
TABLE IV - TOTAL HYDROCARBON EMISSION MEASUREMENTS	12
TABLE V - INSTRUMENTATION TEST	13
FIGURE 1 - WOOD CHIP HEATING SYSTEM	14
FIGURE 2 - SYSTEM SCHEMATIC	15
FIGURE 3 - FLUIDIZED BED FURNACE	16
FIGURES 4-11 - HOME HEATING SYSTEM	17-20
FIGURE 12 - FURNACE EFFICIENCY	21
FIGURES 13-20 - FURNACE TESTING	22-25
APPENDIX I - ECONOMIC POTENTIAL	26
APPENDIX II - CHECKOUT TEST LOG	28

Introduction

The "Fluidized Bed Home Heating Furnace" project is a research and development program sponsored by the U. S. Department of Energy to evaluate a home heating concept employing a unique fluid bed combustor designed to burn wood chips as the fuel. The fluid bed concept promises higher combustion efficiency of the wood resulting in both lower quantities of wood used and significant reductions in emission of air pollutants. This report describes the first year effort in the project. In this initial year, the project has not only contributed to the design and development of the fluidized bed furnace, but has measured the increased combustion efficiency and the reduction in pollutant emissions possible with a fluidized bed furnace in the small size required for home heating.

Residential wood burning is at present the most extensive use of bioenergy in the United States. Sound economic and logistic reasons exist for encouraging the expansion of this trend. Wood is not only cheaper than oil, but could reduce our dependency on imported oil while simultaneously stimulating local industry. However, as with many aspects of modern life, it is also appropriate to review problems with the present technology and consider potential improvements. Current methods of utilizing wood are felt to have two significant problems that stand in the path of continued growth of the use of wood as a home heating fuel.

(1) Air Pollution - Recently, emissions from wood combustion have been identified as including significant quantities of potentially hazardous polycyclic organic matter (POM). The character and quantity of emissions from a wood combustion process are grossly influenced by the design of the combustor, i.e., most of the pollutants are a result of incomplete combustion; hence, significant reduction in the emission level from wood burning is possible by increasing the combustion efficiency.

(2) Convenience - Present designs of wood stoves and fireplaces are certainly not as convenient to use as an oil or gas furnace.

Therefore, to continue the desirable trend of replacing imported oil or scarce natural gas by wood for home heating, it may be concluded that what is needed is a more convenient method of burning wood and, in particular, a method that would provide acceptable emissions of air pollutants.

Why Wood Chips?

Although not currently widely used for home heating, wood chips have great potential.

Automated harvesting techniques of normally unused portions of the tree have been developed by the forest products industry. Studies have shown that

as much as six times the quantity of wood chips can be harvested from a given wood lot as compared to cord wood that is currently used for residential heating in wood stoves or fireplaces. This greatly increased production is based on two factors. First, although normally a forest has a variety of wood species, only selected species are used for lumber or for cord wood. All species,and particularly those unsuitable for lumber,can be used for home heating wood chips. Second, wood chips can be readily made from the whole tree, including branches, twigs and leaves, thus giving more fuel from a given tree than is possible with cord wood.

Automated cutting, handling, delivery and storage techniques could result in delivery of wood to the homeowner at less cost than cord wood. The current price of wood chips is typically half that of cord wood.

Cost and supply factors are certainly sound reasons for using wood chips, however, another factor is of importance to the potential reduction in air pollutants produced by burning wood. When cord wood is used, the wood is put into the furnace on a batch basis, then the air flow to the combustion process is controlled. This results in both fuel-rich combustion and usually in the reduction of combustion temperatures, both of which reduce combustion efficiency and result in increased emissions of particulate matter and gaseous air pollutants. By using small pieces of wood, i.e., wood chips, the flow rate of the wood can be controlled, thus permitting a combustion process having a controlled excess of oxygen, resulting in both maximum recovery of the wood heating value and reduced emissions.

Particulate matter emitted from combustion of wood consists of inorganic ash, carbon char, and condensable organic matter. The amount of carbon char is variable and is generally reflective of combustion efficiency. Usually, condensable organic compounds constitute a significant portion of "particulate matter". This is especially true for inefficient wood burning where condensable organics can typically represent 70% of the particulate matter. Some of the most objectionable by-products of wood combustion are condensable organics, e.g., organic acids, phenols, aldehydes, and polycyclic organic matter (POM). All of the condensable organics can be oxidized to carbon dioxide and water if sufficient oxygen, good mixing, and adequate temperature conditions are present. Hence, efficient combustion tends to minimize emission of condensable organics.

The formation and release of carbon monoxide and volatile hydrocarbons from wood combustion are also related to the efficiency of the combustion process. Thermal degradation of organic material, such as wood, under oxygen deficient conditions is known as pyrolysis. Carbon monoxide, hydrogen, methane, and other volatile hydrocarbons are formed during pyrolysis and, in fact, this is the basis for "wood gasification" processes which convert wood into low BTU fuel gas. These same reactions take place during normal combustion, but if there is sufficient oxygen, good mixing, and adequate temperature conditions, the intermediate "fuel gases" are completely oxidized to carbon dioxide and water. Therefore, again efficient combustion conditions tend to minimize emissions of air pollutants; in this case, carbon monoxide and volatile hydrocarbons.

Typical current residential wood stoves have been measured[1] to produce about 100 grams of hydrocarbons per kilogram of wood burned. The potential for emission reduction can be seen from emission measurements of unburned hydrocarbons during this program of typically 0.5 to 2 grams per kilograms of wood burned.

Finally, wood chips have the significant potential of automating the furnace feed such that the furnace could run unattended for periods approaching that of an oil or gas furnace.

The Fluidized Bed Home Heating System

Figure 1 depicts the major elements of a wood chip heating system incorporating the fluidized bed furnace.

1. Harvesting - Basically, the plant growth need to be reduced to a physical form suitable for automatic handling. The techniques developed by the forest products industry for whole tree chipping appears adequate.

2. Drying and Storage - Wood chip handling and storage techniques developed by the forest products industry would be used combined with rotary kiln or fluidized bed dryers. Wood chip combustion would serve as the energy source for drying.

3. Delivery - The dried wood chips could be delivered to the point of use by pneumatically loaded and unloaded hopper trucks.

4. Fluidized Bed Home Heating System - Figure 2 shows schematically the key features of the tested home heating system utilizing the fluid bed principle. The system consists of five basic components:

    1. A wood feed conveyor.
    2. A fluidized bed furnace including a gas/water heat exchanger and a forced draft fan.
    3. A fabric filter using four 5 inch diameter, inside-out flow, shaker cleaned filter bags, a removable ash container, and an induced draft fan.
    4. A hot water heater to supply domestic hot water to the house. The domestic water is heated by both a gas-fired system and by a wraparound heat exchanger using the hot water output of the fluidized bed furnace. Valves are provided to by-pass the hot water heat exchanger.
    5. An auxiliary heater for supplying space heat to the house when the wood system is not operating. The auxiliary heater incorporates a circulating water pump. Valves are provided to include or bypass the fluidized bed heat exchanger.

---

[1] Knight, C. V. and Graham, M.S., TVA, Emissions and Thermal Performance Mappings for an Unbaffled, Air Tight Wood Appliance, APCA, Louisville, KY, March, 1982.

Figure 3 is a detailed drawing of the fluidized bed furnace fabricated for testing.

The fluid bed is a relatively new approach to the design of combustors. The fluidized bed is formed by flowing air up through a bed of inert particles. The air velocity through the bed and, hence, the pressure drop must be greater than the value required to support the bed weight and less than the value required to sweep the particles out of the bed. The dynamic condition of a fluidized bed is quite analogous to that of a boiling liquid. The function of fluidized inert material is to heat the incoming solid fuel to ignition temperature and to maintain residence time sufficient for combustion of all burnable solid particles within the combustor.

An electrical bed heater for initially bringing the bed up to a temperature adequate to assure ignition of the solid fuel is provided. A natural gas-fired heat up method was also tested.

A furnace control system would be necessary to automatically modulate both the fuel input and the air flow to regulate the furnace output in response to heating demand while maintaining a suitable air-fuel ratio. Such an automatic control system was not provided for the emission testing, manual control was used.

A tubular heat exchange within the combustor was utilized to heat water which would normally be used for home heating. During the performance and emission measurements, the heated water was dumped since testing occurred during the summer months.

The fluid bed heating system as installed for testing is shown in Figure 4. Figure 5 shows the relatively fine wood chips used during the test. The wood chips are carried up a conveyor as shown in Figure 6 and dropped into the furnace as shown in Figure 7. The forced draft fan feeding into the bottom of the fluidized bed furnace is shown in Figure 8. Figure 9 is a photograph of the fabric filter vessel containing four 5 inch diameter filter bags used during the test. Note the induced draft fan at the top of the filter vessel. The induced draft fan exhausts into the chimney as shown in Figure 10. Figure 11 shows the chimney exit during full furnace output. Note that no visible emissions were present.

Testing Program

The experimental fluidized bed home heating system shown schematically in Figure 2 was built. This system was operated to evaluate both the combustion efficiency and the particulate emissions of the system. Additional funding for emission measurements was obtained through the U. S. Environmental Protection Agency. Emission measurements were made by Research Triangle Institute using equipment previously used in wood stove measurements. A report of this testing should be available soon.

The system was instrumented to measure temperatures and flows as shown in Table V. Air velocities were measured using miniature pitot tubes (.125 OD).

Gas samples for Orsat were taken after the heat exchanger and from the stack gases.

Modified EPA Method 5 samples were extracted per EPA procedure and the extracts were analyzed for total chromatographical organics and gravimetric organics as specified in the Trial Protocol for Sampling and Analysis of Emission from Residential Wood Combustion. Samples, extracts, and CH_2Cl_2 washes of process equipment were analyzed for PNAs using glass capillary gas chromatography.

Gas bulb samples were analyzed for CO, CO_2, O_2, and total organic carbon using gas chromatography.

Data was taken to provide analyses of combustion efficiency, both by heat balance and by analysis of the fuel and stack gases. Two sampling series were performed -- one with the combustor operating in a simple cyclone mode, and the second with the combustor in a fluidized bed mode. A representative ash sample from each sampling series was taken and sent out for proximate and ultimate analysis. A representative fuel sample was also analyzed.

The unit was first started up on January 15, 1982. During the remainder of January, a series of checkout tests were made to explore operating characteristics and the rangeability of parameters. Appendix 1 is a log of events during this checkout phase. Some difficulty was initially experienced with achieving uniform feeding of the wood chips and with bringing the unit up to temperature. Changes were made in the wood chip size and in the start-up procedure resulting in reliable, uniform operation for subsequent tests.

Performance and emission measurements were made during 8 separate tests during the weeks starting May 24, 1982 and June 7, 1982. Data collected during these two testing weeks is presented in Table I. Calculated data derived from the measurements is presented in Table II. Calculated data is based on the fuel density and moisture contents presented in Table III and the measured hydrocarbon emission levels presented in Table VI.

Figure 12 presents measured furnace efficiency as a function of heat output. Note that of the measured losses, approximately 1/2 are attributable to the thermal energy content of the stack gases (termed stack losses). Calculations presented in Table II indicate that the majority of the losses other than stack losses are the energy lost in carbon monoxide emissions. It should be noted that the level of CO was typically less than 1%, hence, the precision of the CO measurement is estimated to be no better than $\pm$ 15%.

Figure 13 shows the special emission measuring equipment used. The stack gas sample is drawn from the flue connection (and later from just above the fluid bed) through a heated filter box for non-condensible particulate measurement. Gases then go through the water cooled condenser trap. Condensate was adsorbed in the XAD adsorbent trap.

Figure 14 shows the equipment covered with aluminum foil to prevent decomposition of the collected hydrocarbons by light.

Figure 15 is a close up of the flue gas extraction through the heated filter. Nitrogen oxides were continuously monitored by the equipment shown in Figure 16 and recorded along with furnace temperatures on the equipment shown in Figure 17.

The tested fluid bed distribution plate is shown in Figure 18 along with the transition cone between the 3 inch diameter distributor plate and the 12 inch diameter furnace vessel. The fluid bed with sand in place is shown in Figure 19. Figure 20 shows the furnace modified for the cyclone burner tests.

Testing Results

Tests number 1 and 2 were performed using the fabric filter while for all other tests the bags were removed from the filter vessel. Note in Table IV that the measured hydrocarbon emission level is not significantly different for tests 1 and 2 and for the otherwise identical tests 3 and 4. The ash content (that portion that is incombustible) of wood is typically 0.1% to 0.5%, hence, the maximum uncontrolled emission level of ash is only 1 to 5 g/kg of wood burned. The combination of these two facts result in the recommendation that the heating system be simplified by elimination of the bag filter (and vessel).

Further, note in Table IV that the lowest measured hydrocarbon emission levels were in tests C-1 and C-2 using the cyclone combustor. This rather surprising result suggests that the cyclone should be further investigated as it was noted to have several other advantages including lower pressure drop and ease of start up. On the negative side, the cyclone appeared to require a more uniform feed rate since it does not have the stabilizing thermal mass of the fluidized bed. It was also found to be more difficult to throttle.

It is important to note that the significant reduction in hydrocarbon emission from both combustors tested would reduce (nearly eliminate) the buildup of creosote in the chimney, thus improving the safety aspects of using a wood stove by minimizing the hazards of flue fires.

Conclusions

1) The fluidized bed home heating system was shown to function reliably and controllably during the limited time testing accomplished.

2) Hydrocarbon emission levels of approximately two orders of magnitude less than that of a conventional air tight wood stove were achieved.

3) Furnace efficiencies of typically 70% were measured. Of the 30% inefficiency, approximately 15% was attributable to the thermal energy of the stack gases. Thus, combustion efficiency was typically 85%.

4) The high efficiency and low emission levels measured using the cyclone combustor indicate that this configuration should be further investigated before a final selection is made.

5) Test results suggest that the fabric filter included in the system is not justified.

6) The tested home heating system offers significant improvements in efficiency and emission levels and merits further development testing. Modifications to permit automated, continuous operation should be the next development objective.

TABLE I

AVERAGED TEST DATA

TEST NUMBER	1	2	3	4	C-1	C-2	AB-1	AB-2
DATE	5/26	5/26	5/27	5/28	6/8	6/8	6/9	6/10
CONFIGURATION	FB	FB	FB	FB	Cycl	Cycl	FB	FB
GAS TEMPS, ^{o}F								
Bed	1520	1574	1589	1641	1711	1782	1583	1715
Above Bed	1544	1606	1603	1198	1266	1398	1642	1555
Furn. Out	278	240	254	272	330	332	361	352
Stack	183	159	162	171	184	188	226	222
WATER ΔT, ^{o}F	60.2	45.3	51.3	55.5	52.8	55.8	67.7	63.7
WATER FLOW, GPM	1.60	1.68	1.62	1.60	1.60	1.60	1.78	1.80
FUEL FLOW, $Ft.^{3}/Hr.$	.492	.334	.388	.481	.409	.397	.613	.583
FAN SETTING, FD	26	26	26	26	20	23	26	26
ID	65	59	50	50	36	36	55	55
PITOT ΔH, $IN\text{-}H_2O$								
INLET	.055	-	-	.085	-	-	.123	.135
OUTLET	.230	-	-	.33	.24	.29	.61	.64
STACK	.044	.018	.04	.040	.031	.025	.070	.080
ORSAT								
CO_2			4.5	8.3	8.0	6.8	7.6	9.6
O_2			13.6	11.2	10.0	13.2	12.9	8.4
CO	1.3*	1.3*	2.4	0.9	0.8	0.5	0.9	2.0

* Average value

TABLE II

CALCULATED DATA

TEST NO.	1	2	3	4	C-1	C-2	AB-1	AB-2
DATE	5/26	5/26	5/27	5/28	6/8	6/8	6/9	6/10
CONFIGURATION	FB	FB	FB	FB	CY	CY	FB	FB
VOL. FLOWS, ACFM								
INLET	13.2	-	-	16.4	-	-	19.7	20.6
OUTLET	49.4	-	-	58.9	52.2	57.4	84.8	86.4
STACK	45.4	28.5	42.6	42.9	38.2	34.4	59.2	63.1
WT. FLOW, LB/HR.								
FUEL	9.84	6.68	7.76	9.62	8.18	7.94	12.26	11.66
AIR	60.6	-	-	75.3	-	-	90.4	94.6
OUT	160	-	-	192	157	173	246	254
STACK	169	110	163	162	141	126	206	220
HEAT IN, BTU/HR.	73,300	49,700	57,800	71,600	60,900	59,100	91,300	86,800
HEAT OUT, BTU/HR.	48,200	38.100	41,600	44,400	42,200	44,600	60,300	57,300
LOSS MEASURED	25,100	11,600	16,200	27,200	18,700	14,500	31,000	29,500
EFFICIENCY	66	77	72	62	69	75	66	66
STACK LOSS, BTU/HR.	8,050	5,200	8,350	9,390	9,880	10,970	17,320	17,330
CO LOSS, BTU/HR.	8,460	5,310	14,640	5,520	4,360	2,470	7,640	18,100
HC LOSS, BTU/HR.	220	270	320	380	20	5	100	330
"CALC LOSS", BTU/HR.	16,730	10,780	23,310	15,290	14,280	13,445	25,060	35,760
MEASURED LOSS / CALC. LOSS	1.50	1.08	.70	1.78	1.30	1.08	1.23	.82

TABLE III

FUEL CHARACTERISTICS

MOISTURE CONTENT:

Run #1 = 11.7%
Run #2 = 10.9%
Run #3 = 10.9%

Average Moisture = 11.2%

DENSITY MEASURED:

0.24 g/ml = 15 lb./ft.^{3}

CALCULATED HEATING VALUE:

Assumed dry, average value = 8500 btu/lb.

Heating value corrected for 11.2% moisture = 7445 btu/lb.

Volume Heating Value = 111,700 btu/ft.^{3}

TABLE IV

TOTAL HYDROCARBON (BOILING POINT OVER 100° C)

EMISSION MEASUREMENTS:

TEST NUMBER	HYDROCARBONS	
	Mg/FT.^{3}	gm/KG of Wood*
1	2.046	1.25
2	3.656	2.06
3	2.838	2.06
4	3.357	1.98
C-1	0.233	0.14
C-2	0.053	0.03
AB-1	0.651	0.41
AB-2	1.974	1.41

*Comparable air-tight wood stove emission is about 100 grams/kilogram of wood.

TABLE V

INSTRUMENTATION LIST

Parameter	Name	Range
T_1	Ambient Temp.	50 - 100°F
T_2	Furnace Out Temp.	50 - 300°F
T_3	Filter Out Temp.	50 - 300°F
T_4	Bed Temp.	50 - 1800°F
T_5	Freeboard Temp.	50 - 1800°F
T_6	Water In Temp.	50 - 200°F
T_7	Furnace Water Out	50 - 200°F
T_8	Heater Water Out	50 - 200°F
ΔP_1	Inlet Air Pitot	0 - 3 In - H_2O
ΔP_2	Furnace Out Pitot	0 - 3 In - H_2O
ΔP_3	Filter Out Pitot	0 - 3 In - H_2O
ΔP_4	Furnace Inlet Pressure	0 - 10 In - H_2O
ΔP_5	Furnace Outlet Pressure	0 - 10 In - H_2O
FW	Water Flow	0 - 10 GPM
S_1	Freeboard Gas Sample	
S_2	Furnace Out Gas Sample	
S_3	System Out Gas & Particulate Sample	

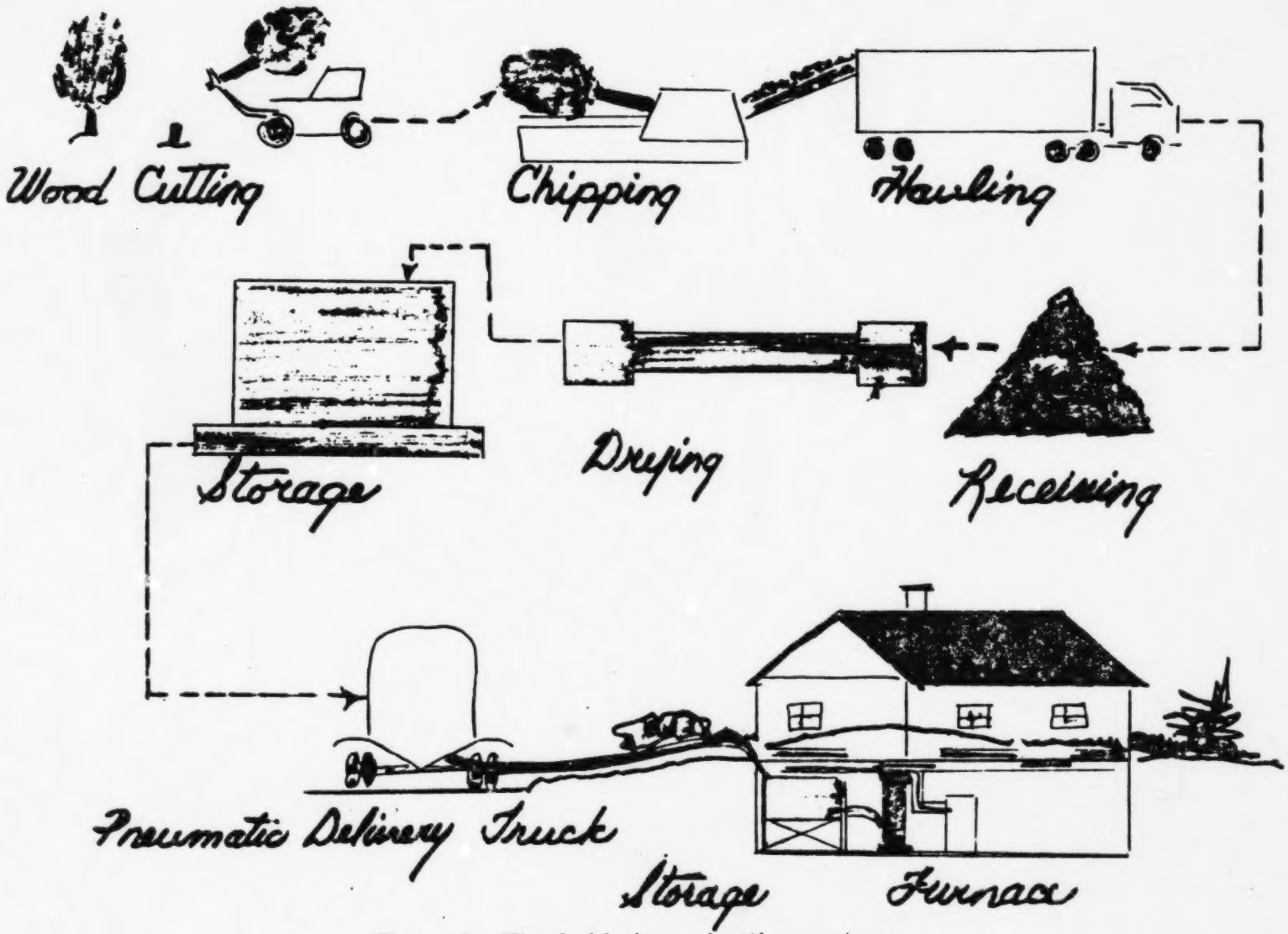


Figure 1. Wood chip home heating system.

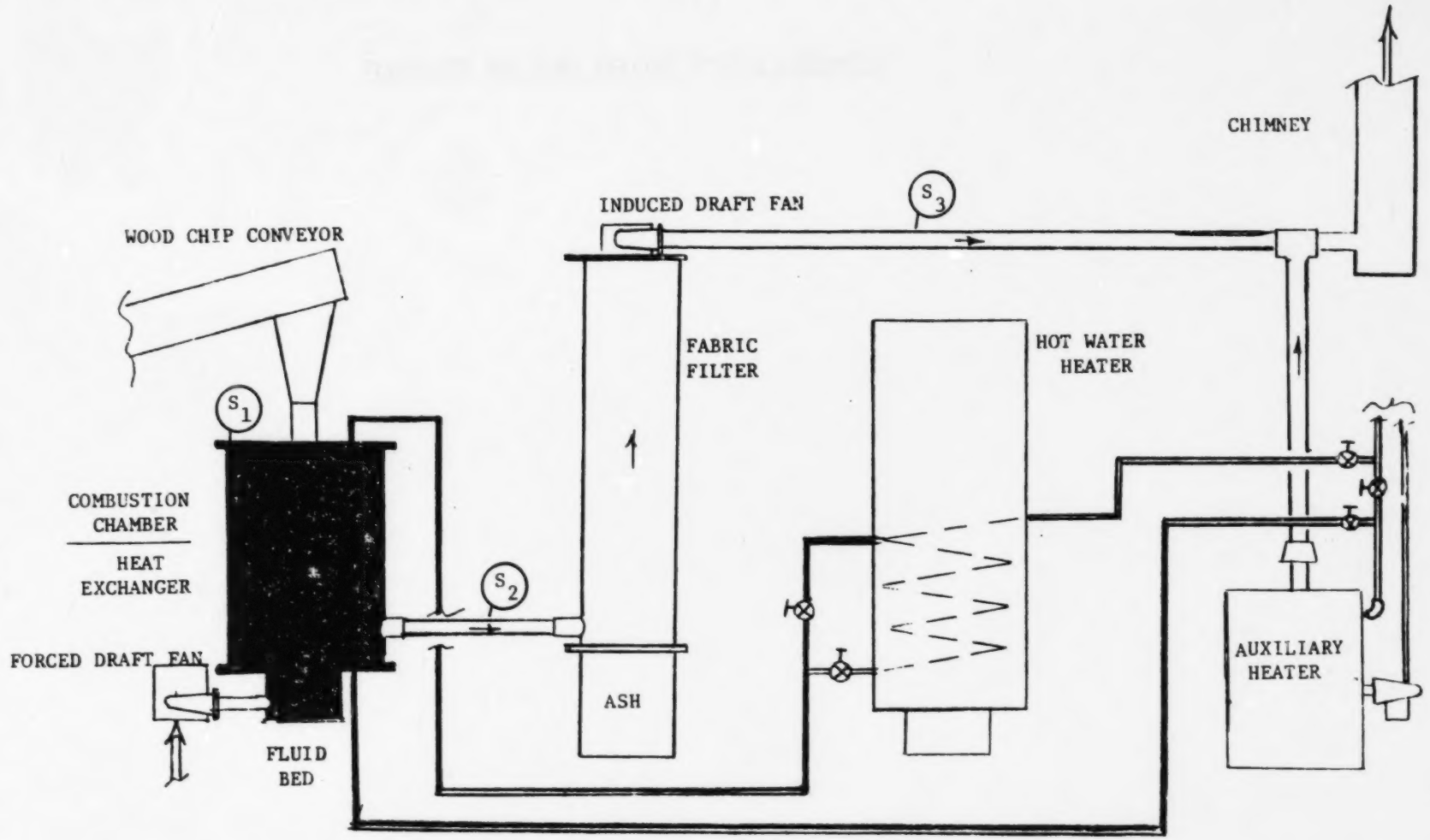


Figure 2. Fluidized-bed home heating system schematic.

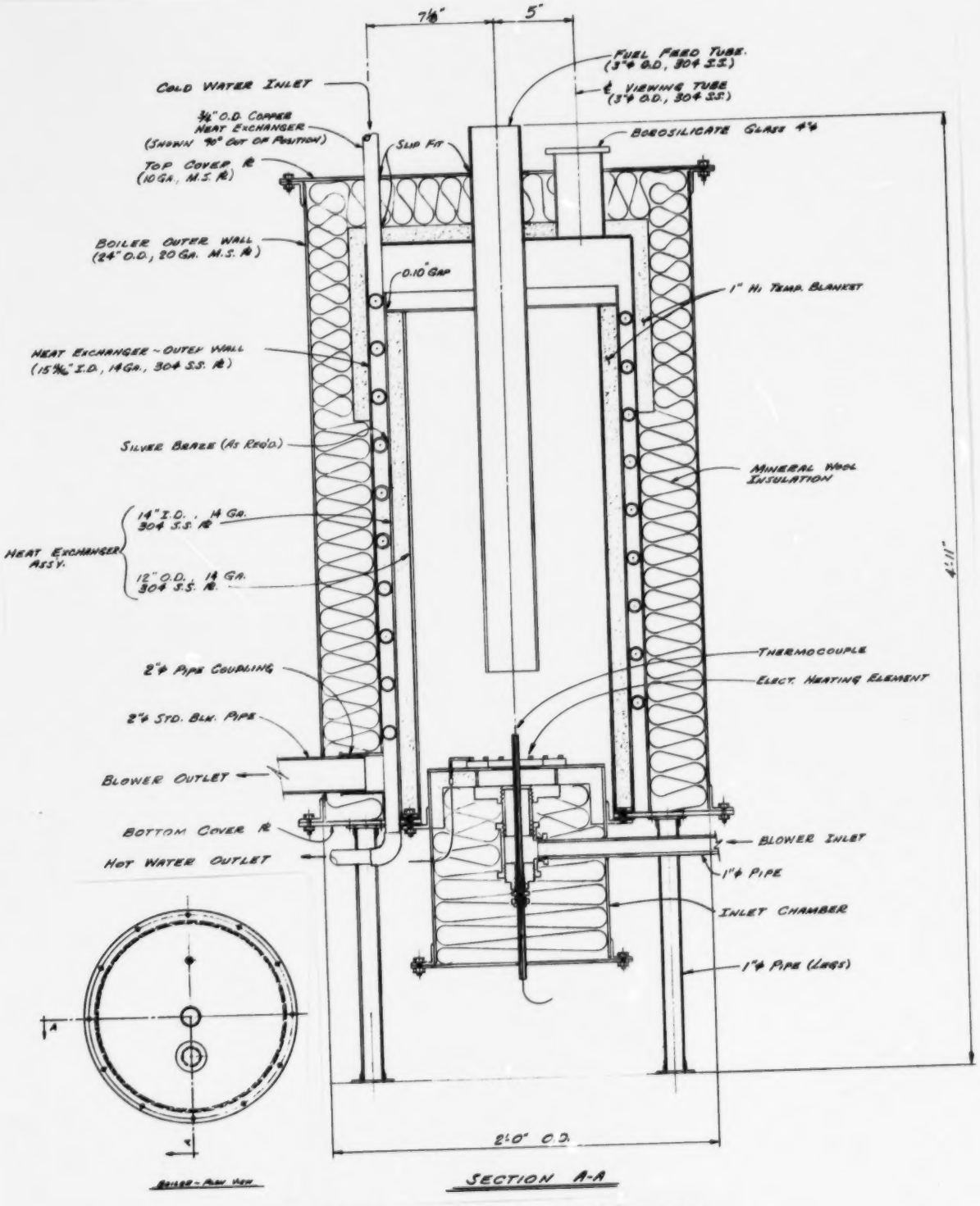


Figure 3. Fluidized-bed furnace.

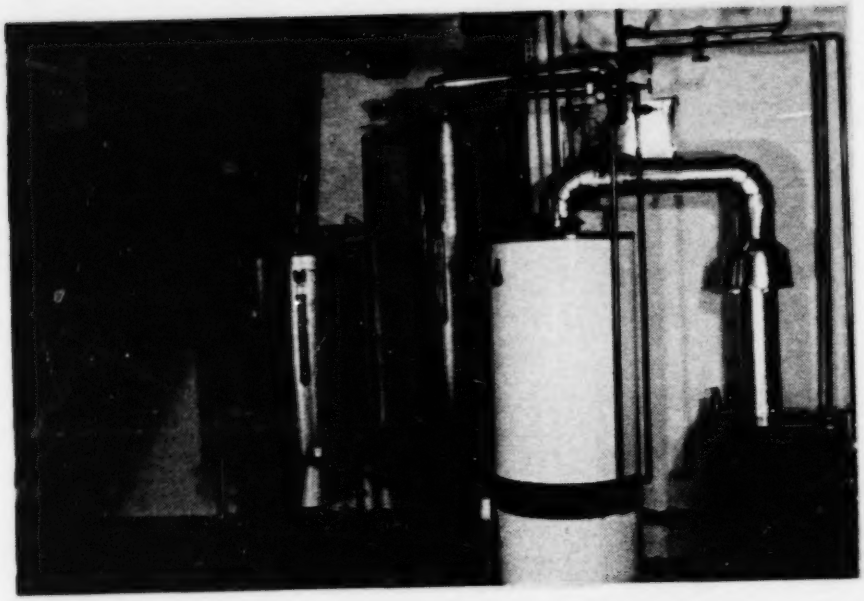


Figure 4
Fluidized Bed Home Heating System

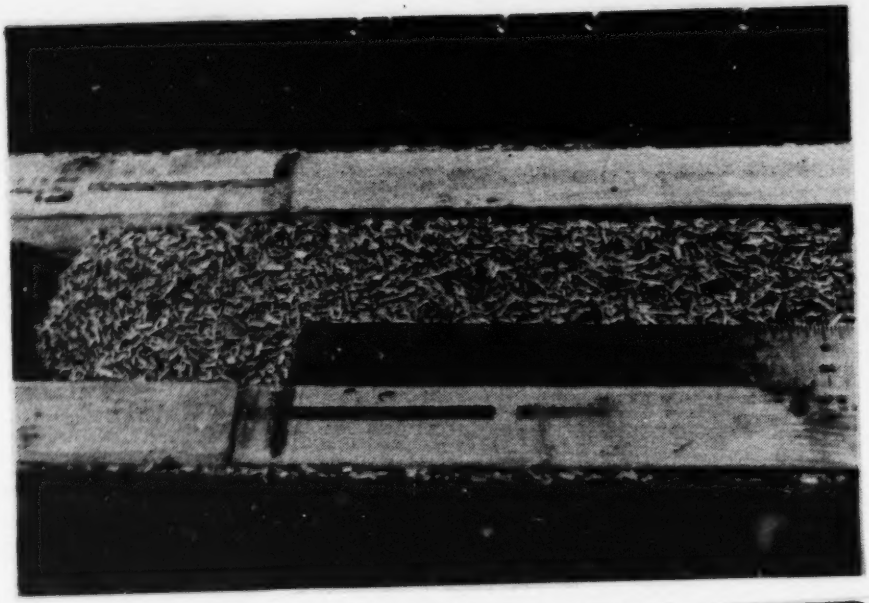


Figure 5
Tested Wood Chips

Reproduced from best available copy.

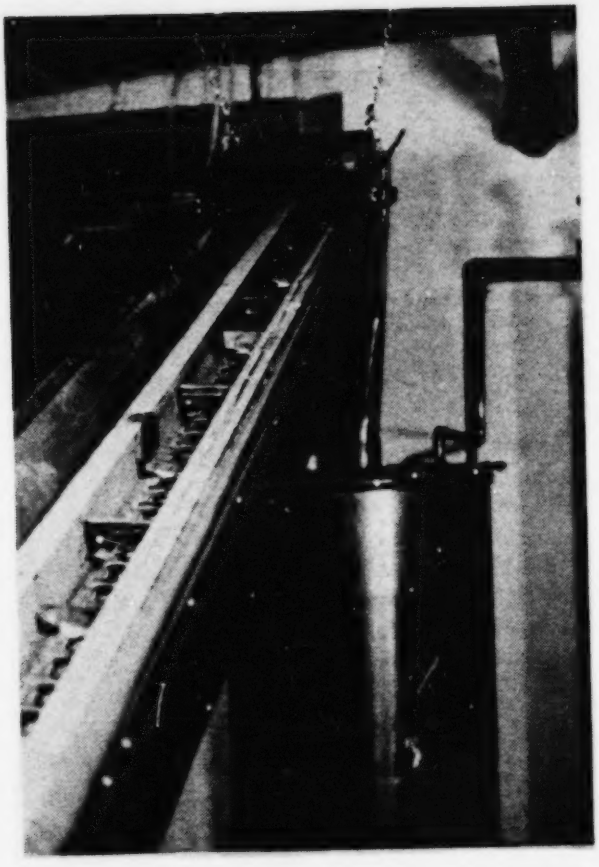


Figure 6
Wood Chips Conveyor

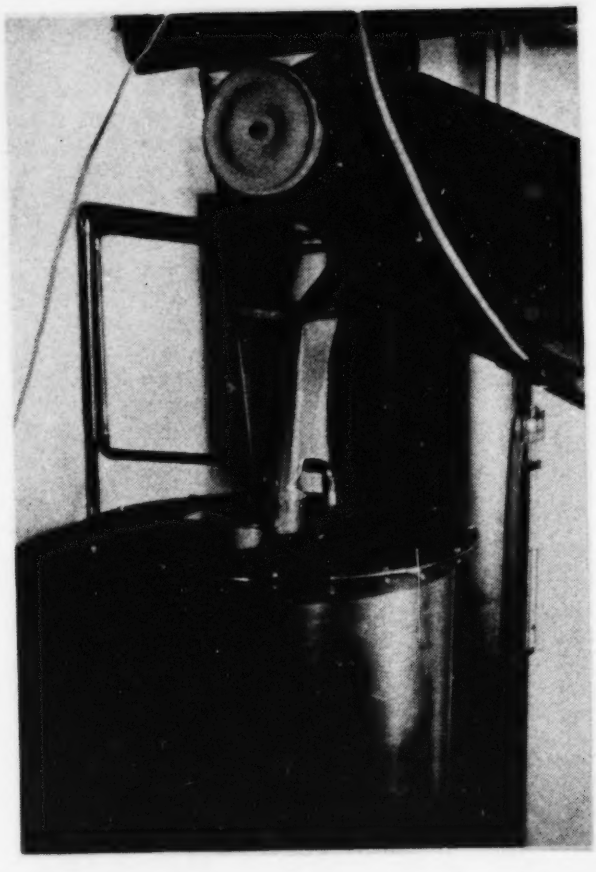


Figure 7
Gravity Feed
Into Furnace

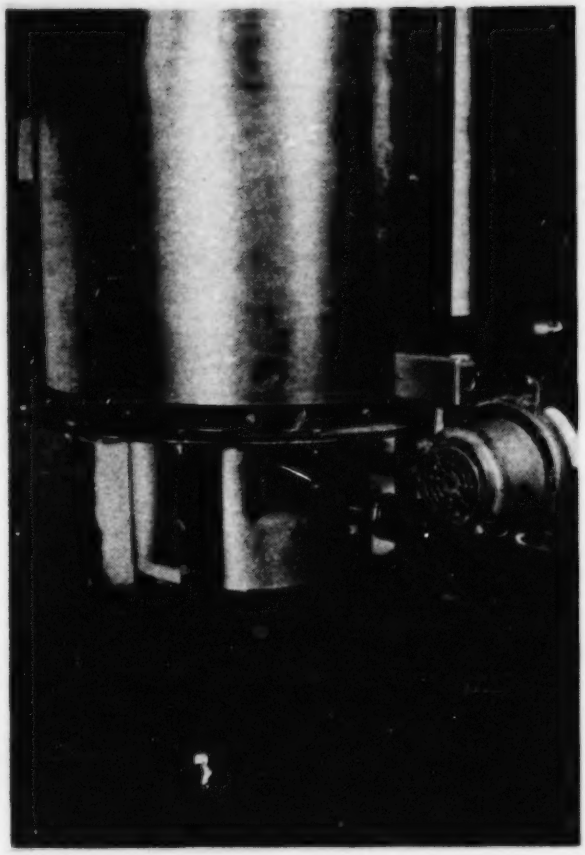


Figure 8
Fluid Bed Forced
Draft Fan

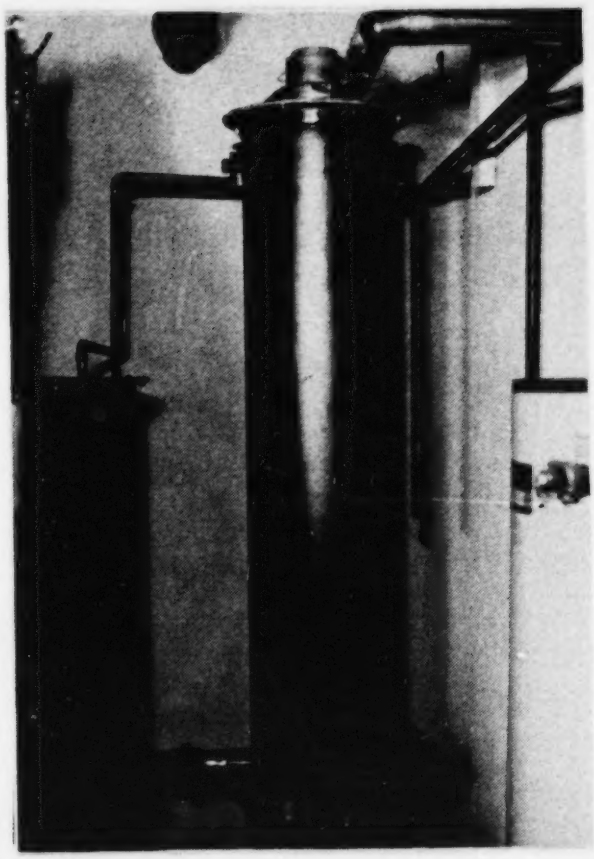


Figure 9
Fabric Filter and Induced
Draft Fan

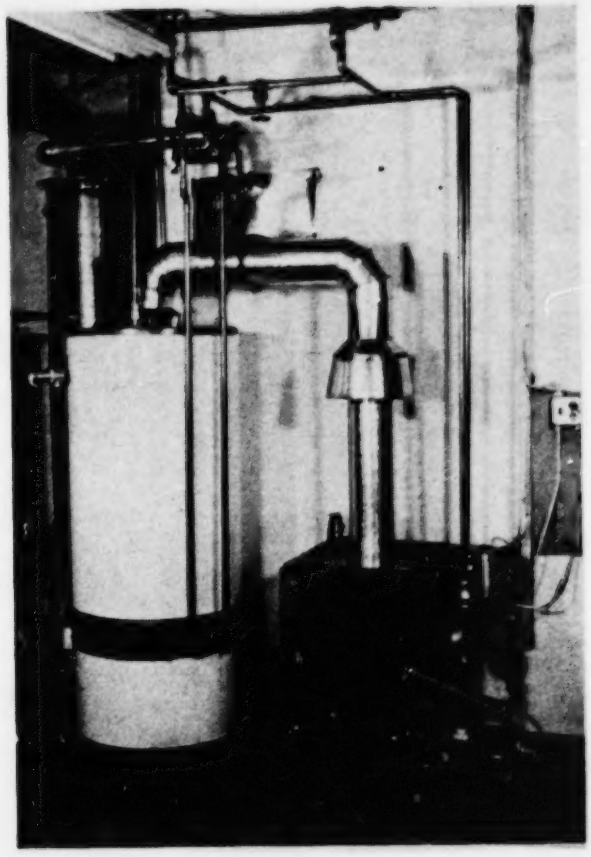


Figure 10
Auxiliary Hot Water Heater

Figure 11
No Visible Emission
During Full Output

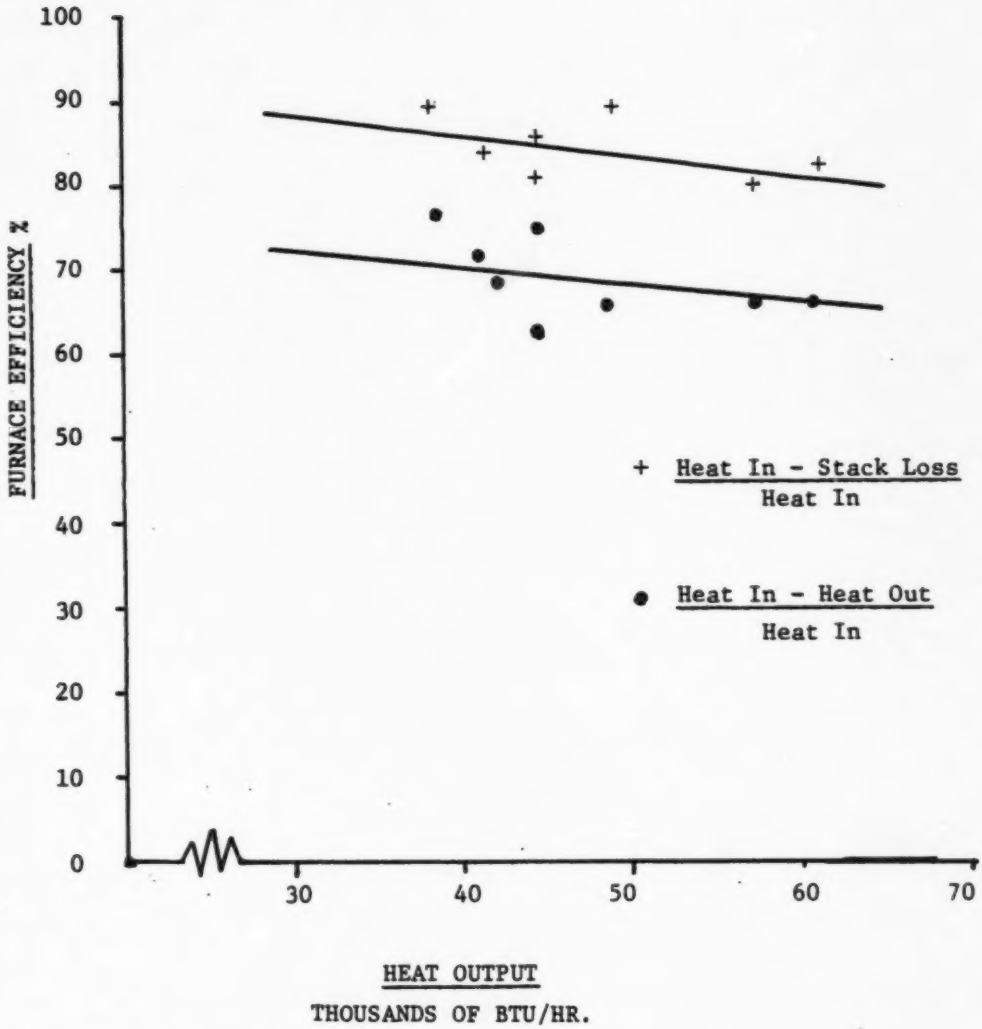


Figure 12. Furnace efficiency.

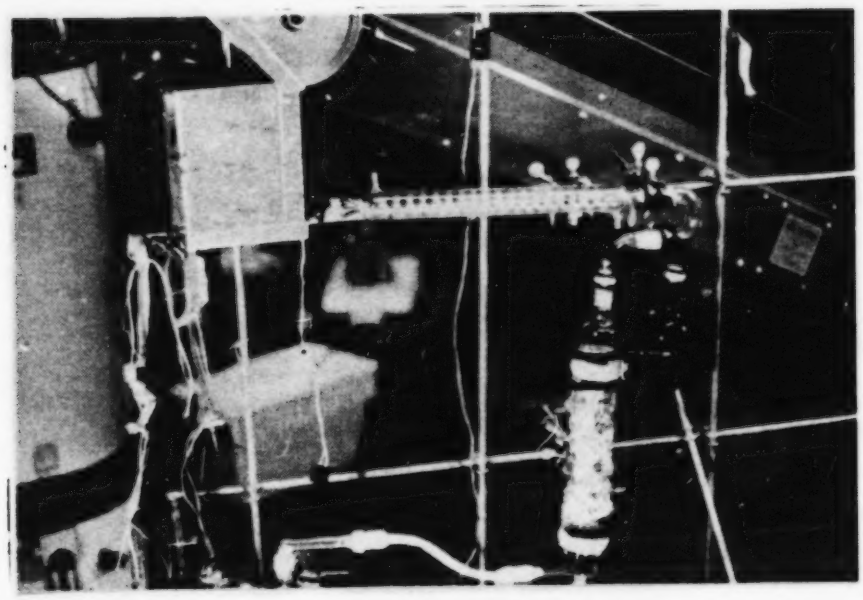


Figure 13
Emission Measurement Equipment

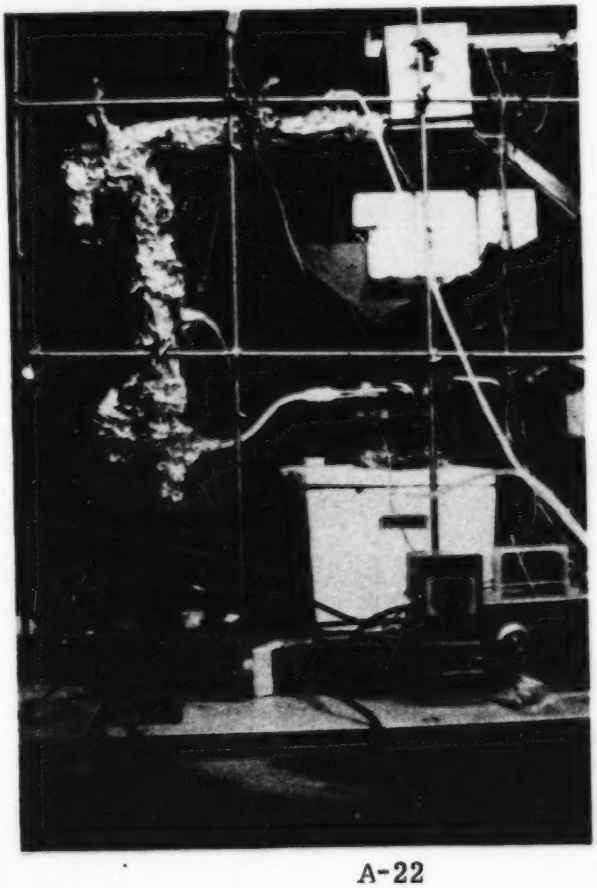


Figure 14
Foil Covering For
Light Shielding

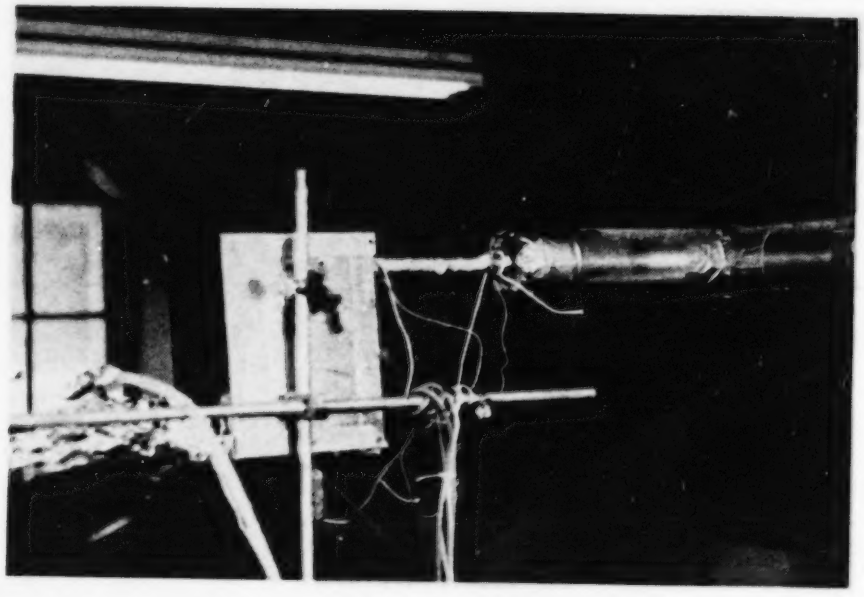


Figure 15
Flue Gas Extraction Line and Heated Particulate Filter

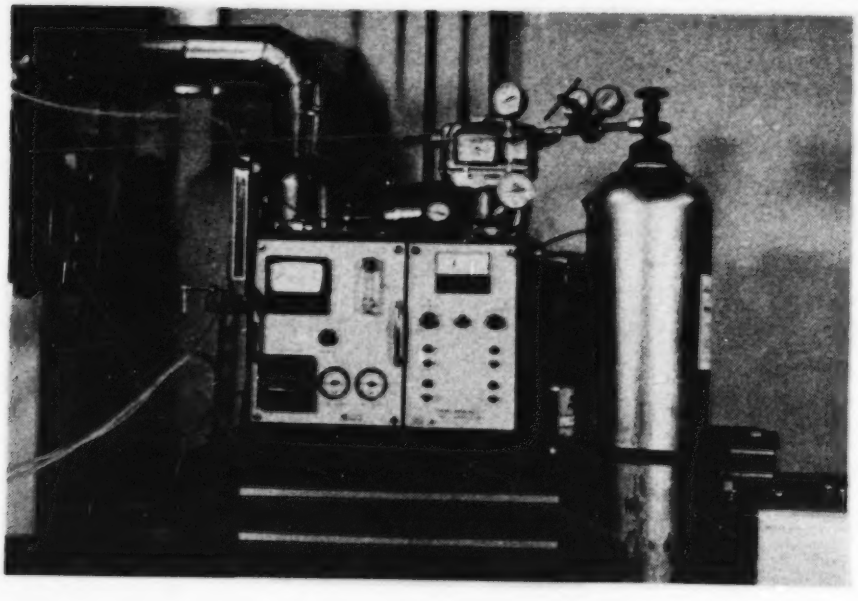


Figure 16
Continuous NO_x Monitor

Reproduced from
best available copy.

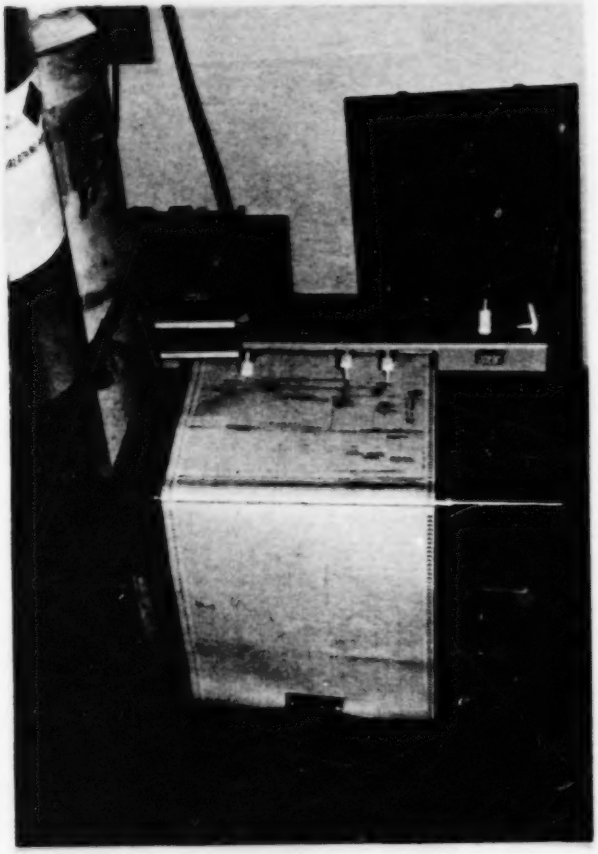


Figure 17
Recorder for NO_x and
Fluid Bed Temperature

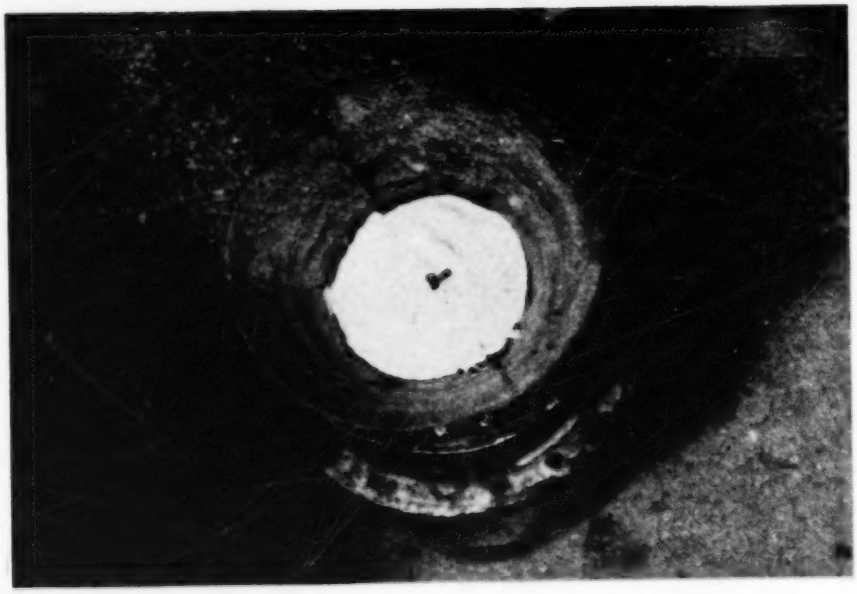


Figure 18
Fluid Bed Distributor Plate and Cover

Figure 19
Fluid Bed of Sand

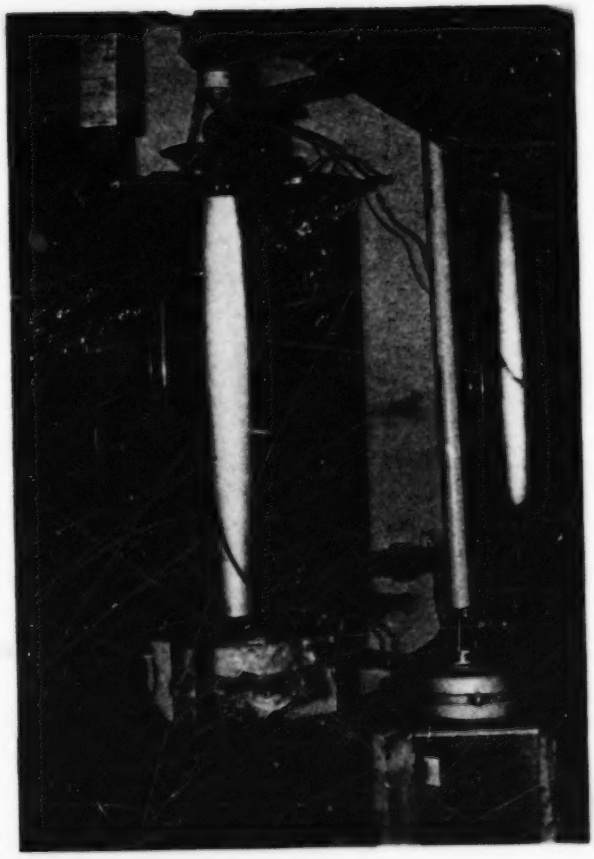


Figure 20
Furnace With Cyclone
Burner Installed

APPENDIX I

Economic Potential

A key question as to the technical and economic desirability of the proposed home heating system is: Are existing forests a significant fuel source relative to current and future energy requirements? To answer this question, consider first that lumber companies have found that a well managed forest will grow at least 2 tons of dry wood per acre a year, depending on local factors such as rainfall and sunshine. There are about 500 million acres of forest in the United States. Using a heating value of 8,500 BTU per pound of dry wood results in a potential of 17 quadrillion BTU's per year. In addition to this potential fuel from existing forests, various plant waste products could be used as fuels including agriculture waste. Altogether the heating value of waste materials in the United States was estimated at 8.6 quadrillion BTU in 1970. Hence, a renewable fuel source of 25.6 quadrillion BTU's exists now. The significance of these numbers can be seen by comparison with anticipated energy use rates estimated in another recent study:

Sector	Quadrillion BTU's 1980	2000
Household and Commercial	17.5	21.9
Industrial	24.8	39.3
Transportation	22.8	42.6
Electrical Generation	28.0	80.4

It can be concluded that wood and other plant growth, together with waste products from plant growth, are indeed a significant potential energy source; an existing, renewable resource that is larger than that anticipated to be used annually in household and commercial heating through the year 2000.

The economic potential to the homeowner of using wood chips may be seen from the following comparison:

Item	Typical Current Price	Heating Value	Unit Price($MM BTU)
Wood Chips	$19.00/Green Ton	5,500 BTU/Lb.	1.73
Cord Wood	$90.00/Cord	6,000 BTU/Lb.	3.75
Oil	$ 1.30/Gallon	140,000 BTU/Lb.	9.28

Using these current prices and estimated use efficiencies, the following estimates of home heating costs are made for an annual requirement for a typical home of 140 million BTU's (1,000 gallons of oil):

Type	Combustion Efficiency	Furnace Efficiency	$/Year
Oil	97	80	1,300
Wood Stove	70	80	750
Wood Chip System	99	80	244

APPENDIX II

CHECKOUT TEST LOG

January 15, 1982 (First start-up)

1) Both heaters on, preheat to 1000°F sand temp (Bottom heater limited to 1500°F)
2) Wood feed initiated, ignition achieved
3) Sand level dropped, add more sand, reheat
4) ID fan runaway (speed controller failure)

January 18, 1982

1) Installed variac for ID fan control
2) Preheat as before
3) Wood feed on at sand temperature of 1200°F
4) Sand temperature increased to 1500°F
5) Heat exchanger overheated - solder failure (caused by water bypass valve being open)
6) Repair heat exchanger

January 19, 1982

1) Start-up after preheat
2) FD fan runaway (another speed control failure)

January 20, 1982

1) Run from 9:00 am to 11:15 am
2) Sand temperatures and above sand = 1350 to 1450°F
3) Outlet temperature = 190 to 215°F
4) No visible smoke from chimney
5) Water temperature about 140°F
6) House temperature held at 75°F (35°F outside)

January 21, 1982

1) As check on effects of fluidized bed, removed sand such that distributor plate was bare
2) Turned on top heater, when red hot start wood
3) Run from 1:30 pm to 3:30 pm

   - Much smoke during start-up; temperature unstable (1100-1800°F)
   - Water temperature 90° to 110°
   - Still no visible smoke from chimney after start-up

January 25, 1982

9:30 am Both heaters on, added 2 quarts sand

T1 = Tempeature under disc heater, °F
T1*= Temperature above sand, °F
T2 = Sand Temperature, °F
T3 = Water Outlet Temperature, °F

Time	T1	T2	T3	Remarks
9:30	84	84	140	Heaters on
9:45	1187	377	154	
10:00	1420	810	121	
10:07	1507	979	114	Bottom heater off
10:08	102*	1015	113	Start air and wood feed
10:11	169*	398	112	No ignition
10:13	1188	456	112	Bottom heater on
10:35		1128	105	Fluidized, ignition, died
10:36	208*	440		
11:03	265*	(1143-544)	95	Try again
12:12	1282*	1003	100	Heaters off, conv. 6.5
12:15	1403	1180	105	
12:21	1581	1312	111	Conv. 7.0
12:27	1574	1335	120	
12:31	1650	1385	126	
12:40	1685	1320		Conveyor off
12:45	1300	1123		
12:46	1136	932		FD Fan Off

January 26, 1982

Installed fluid bed and filter pressure gauges. Removed 4 1/4 pints of sand, distributor plate visible; added 1 pint sand, DP and coil not visible; heaters on at 10:00 a.m.

Time	T1	T2	T3	ΔP_b	ΔP_f	Remarks
10:23	1180	347	107			
10:27	1256	449	104			
10:39	1435	699	110			
10:45	1494	769	104			Pump on
10:59	1470	913	98			Coil red
Ignition okay, but distributor plate soon visible, added 1 pint of sand keeping on conveyor - died out, reheat						
11:35	1159*	1000	165			Gas on
11:37	1260	1146	161			Gas off
Added another 1/3 pint sand						
11:57	1450	1020	135	3.5	2.0	
12:01	1492	1165	136	3.0		
Reheat						
1:43	1170	849	131	2.3		FD = 20%
1:45	1292	8 to 1100	139	2	5.6	ID = 80%
2:06	1455	5 to 1200	139	2	5.6	
Defluidization occurring; added 2/3 pint sand						
2:32	1367	1095	139		6.5	FD = 90%
2:38	1564	6 to 1200	145			
2:44	1650 to 1720	1300	152		7.0	FD =100%

Appendix B

Additional Data

TABLE B-1. EMISSION RATES, PAH COMPOUNDS (mg/hr)

Compound	Test							
	FB-1	FB-2	FB-3	FB-4	C-1	C-2	FB-5	FB-6
Naphthalene	153.53	151.68	151.81	157.51	3.38	19.78	241.52	1,708.34
Biphenyl	13.08	27.14	42.83	37.65	1.45	0.43	4.45	73.45
Fluorene	43.70	65.27	80.35	93.72	0.68	0.83	7.28	69.48
Phenanthrene	197.96	53.98	108.41	231.23	12.73	3.61	32.68	259.35
Anthracene	42.17		111.01	93.85	0.35		2.16	12.42
Carbazole	0.59	ND	1.33	1.38	0.07	ND	0.03	ND
1-Methylphenanthrene	22.67	37.46	62.71	21.77	1.39	2.54	10.30	43.15
9-Methylanthracene	1.89	1.13	1.94	1.23	ND	0.20	ND	ND
Fluoranthene	113.29	51.84	95.40	231.52	3.30	2.44	17.12	95.80
Pyrene	78.22	56.79	137.45	247.74	5.02	2.06	21.49	113.78
Benzo(a)anthracene	12.24	2.29	27.56	68.08	1.05	0.17	ND	ND
Chrysene	9.17	1.45	17.50	37.86	0.16		ND	ND
12-Methylbenz(a)anthracene	0.09	0.21	0.06	2.69	ND	0.12	ND	0.34
7-Methylbenz(a)anthracene	0.87	ND	0.95	1.47	ND	0.06	0.19	1.56
7,12-Dimethylbenz(a)-anthracene	ND	ND	ND	ND	ND	ND	ND	ND
Benzo(b,k)fluoranthene	0.42	ND	34.99	93.07	ND	ND	ND	ND
Benzo(e)pyrene	0.89	ND	20.66	49.50	ND	ND	0.26	4.76
Benzo(a)pyrene	1.96	0.14	37.65	111.70	ND	ND	1.80	
Perylene	0.13	0.05	2.84	5.75	ND	ND	3.50	3.64
3-Methylcholanthene	ND	ND	ND	ND	ND	ND	ND	ND
Indeno(1,2,3-cd)pyrene	ND	ND	ND	2.66	ND	ND	ND	ND
Dibenz(a,h)anthracene	ND	ND	ND	ND	ND	ND	ND	ND
Benzo(g,h,i)perylene	ND	ND	ND	ND	ND	ND	ND	ND

ND = Not detected.

TABLE B-2. PAH CONCENTRATIONS IN FLUE GAS (μg/m³)

Compound	Test							
	FB-1	FB-2	FB-3	FB-4	C-1	C-2	FB-5	FB-6
Naphthalene	2,717.79	4,127.33	2,511.31	1,897.01	71.16	468.23	3,548.60	23,826.27
Biphenyl	231.54	738.39	708.48	692.54	30.54	10.17	65.45	1,023.93
Fluorene	773.67	1,776.18	1,329.14	1,723.66	14.29	19.58	107.01	968.57
Phenanthrene	3,504.39		1,793.45	4,252.86	268.07		480.15	3,615.70
Anthracene	746.42	1,468.80	1,836.36	1,726.19	7.29	85.46	31.68	173.14
Carbazole	10.52	ND	22.05	25.42	1.47	ND	0.39	ND
1-Methylphenanthrene	401.26	1,019.28	1,037.42	400.48	29.37	60.24	151.40	601.57
9-Methylanthracene	33.47	30.77	32.14	22.61	ND	4.82	ND	ND
Fluoranthene	2,005.4	1,410.62	1,578.10	4,258.16	69.51	57.82	251.53	1,335.55
Pyrene	1,384.65	1,545.40	2,273.82	4,556.53	105.61	48.66	315.77	1,586.24
Benzo(a)anthracene	216.63	62.44	455.87	1,252.22	22.01		ND	ND
Chrysene	162.28	39.54	289.45	696.25	3.44	4.02	ND	ND
2-Methylbenz(a)anthracene	1.58	5.71	1.07	49.51	ND	2.82	ND	4.72
7-Methylbenz(a)anthracene	15.47	ND	15.77	27.00	ND	1.31	2.79	21.77
7,12-Dimethylbenz(a)-anthracene	ND	ND	ND	ND	ND	ND	ND	ND
Benzo(b,k)fluoranthene	7.49	ND	576.86	1,711.84	ND	ND	ND	ND
Benzo(e)pyrene	15.74	ND	341.69	910.51	ND	ND	3.75	66.34
Benzo(a)pyrene	34.79	3.72	622.78	2,054.35	ND	ND	26.49	
Perylene	2.23	1.31	46.96	105.81	ND	ND	51.39	50.73
3-Methylcholanthene	ND	ND	ND	ND	ND	ND	ND	ND
Indeno(1,2,3-cd)pyrene	ND	ND	ND	ND	ND	ND	ND	ND
Dibenz(a,h)anthracene	ND	ND	ND	49.00	ND	ND	ND	ND
Benzo(g,h,i)perylene	ND	ND	ND	ND	ND	ND	ND	ND

ND = Not determined.